

UNCLASSIFIED

AD 103663

Armed Services Technical Information Agency

Reproduced by

DOCUMENT SERVICE CENTER

KNOTT BUILDING, DAYTON, 2, OHIO

This document is the property of the United States Government. It is furnished for the duration of the contract and shall be returned when no longer required, or upon recall by ASTIA to the following address: **Armed Services Technical Information Agency, Document Service Center, Knott Building, Dayton 2, Ohio.**

NOTICE: WHEN GOVERNMENT OR OTHER DRAWINGS, SPECIFICATIONS OR OTHER DATA ARE USED FOR ANY PURPOSE OTHER THAN IN CONNECTION WITH A DEFINITELY RELATED GOVERNMENT PROCUREMENT OPERATION, THE U. S. GOVERNMENT THEREBY INCURS NO RESPONSIBILITY, NOR ANY OBLIGATION WHATSOEVER; AND THE FACT THAT THE GOVERNMENT MAY HAVE FORMULATED, FURNISHED, OR IN ANY WAY SUPPLIED THE SAID DRAWINGS, SPECIFICATIONS, OR OTHER DATA IS NOT TO BE REGARDED BY IMPLICATION OR OTHERWISE AS IN ANY MANNER LICENSING THE HOLDER OR ANY OTHER PERSON OR CORPORATION, OR CONVEYING ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE OR SELL ANY PATENTED INVENTION THAT MAY IN ANY WAY BE RELATED THERETO.

UNCLASSIFIED

AD No. 103663

ASTIA FILE COPY

INTERSERVICE VEHICLE MOBILITY SYMPOSIUM
(Unclassified)

VOLUME 1

MINUTES, ABSTRACTS, AND DISCUSSIONS OF THE SYMPOSIUM

FC

held at

Stevens Institute of Technology.
Hoboken, New Jersey

18-20 April 1955

Conducted by the Office of Ordnance Research
for the Corps of Engineers, Transportation Corps,
and the Ordnance Corps of the U. S. Army

Office of Ordnance Research, U. S. Army
Box CM, Duke Station
Durham, North Carolina

Volume Two, containing reprints of papers presented at the Symposium, will be distributed by the Land Locomotion Research Laboratory, Detroit Arsenal, Center Line, Michigan.

ERRATA

Pages 35, 36, 37 should follow Page 13.

Pages 40, 41, 42 have been deleted.

CONTENTS

	<u>Page</u>
<u>Part One</u>	
Addresses	
Opening Remarks	
Col. P. N. Gillon, Office of Ordnance Research	i
Dr. George Glockler, Office of Ordnance Research	ii
Program	iii
Post-Symposium Reflections	
Lt. Col. M. G. Bekker, Detroit Arsenal	vii
Summation of the Symposium	
Mr. R. J. Jackson, Corps of Engineers	x
Lt. Col. M. R. Brice, Detroit Arsenal	xi
Lt. Col. M. G. Bekker, Detroit Arsenal	xii
Banquet Address	
Mr. Carl L. Hecker, Oliver Corporation	xvi
Closing Remarks	
Dr. George Glockler, Chief Scientist, Office of Ordnance Research	xxi

Part Two

Abstracts and Discussions

Summary of Work on Vehicle Mobility in the United Kingdom	1
Mr. F. L. Uffelman, The Fighting Vehicle Research and Development Establishments of the British Ministry of Supply	
A Review of Soil and Snow Trafficability	2
Mr. C. R. Foster and S. J. Knight, Corps of Engineers	
Transportation Corps in the Field of Mobility	8
Mr. H. P. Simon, Transportation Corps	
A Proposed System of Physical and Geometrical Terrain Values for the Determination of Vehicle Performance and Soil Trafficability	13
Lt. Col. M. G. Bekker, Detroit Arsenal	

Application of Recent Developments in Visco-Elasticity and Plasticity to Problems in Soil Mechanics Professor E. H. Lee, Brown University	14
Dimensional Analysis and Scale-Model Testing in Mobility Research Mr. C. J. Nuttall, Wilson, Nuttall, Raimond Engineers, Inc. Dr. J. P. Finelli, Stevens Institute of Technology	16
Methods of Evaluating the Effects of Terrain Geometry on Vehicle Mobility Professor I. J. Sattinger, University of Michigan	23
Development of New Track Concepts by the Ordnance Corps Col. G. T. Petersen, Detroit Arsenal	29
A Radical Improvement in the Design of Tracked Vehicles Mr. J. R. Doyle, Oliver Corporation	38
The Effects of Power Plants upon Vehicle Mobility Dr. E. T. Vincent, University of Michigan	43
Analysis of a Highly Variable Torque Powerplant for Cross-Country Vehicles Dr. W. I. E. Kamm, Stevens Institute of Technology	48
Mobility Evaluation by Means of Field Tests in Soft Terrains Mr. C. W. Wilson, Wilson, Nuttall, Raimond Engineers, Inc.	52
The Performance of Tracked and Wheeled Vehicles in Snow Mr. J. G. Thomson, Canadian Defense Research Board	56
Mobility Problems of the Navy in the Arctic Mr. John T. Tucker, U. S. Naval Engineering	59
A Review of Corps of Engineers - Air Force Studies on Flotation Landing Gear Mr. F. M. Mellinger, Corps of Engineers Mr. J. P. Sale, Corps of Engineers	61
Mobility Improvement for USAF Aircraft and Missile Ground Support Equipment Lt. J. H. Frye, Wright Air Development Center	66
Mobility - Tire Mr. Willard D. England, Detroit Arsenal	67
Vehicle Design Concepts Most Adaptable to Highway Bridges Mr. E. L. Erickson, Bureau of Public Roads	69

Vehicle Design Concepts Most Adaptable to Highway Pavements Mr. Fred Burggraf, Highway Research Board	70
Shore Trafficability as Related to Environment Mr. R. L. Wiegel, University of California Dr. Parker D. Trask, University of California	71
Effect of Geologic and Geographic Factors on Soil Trafficability Dr. Parker D. Trask, University of California	75
Curriculum of Automotive Engineering Dr. E. T. Vincent, University of Michigan	76
Scope of Activities in Land Locomotion Research from an Automotive Point of View Lt. Col. L. S. Nelson, Detroit Arsenal	80

PART ONE

ADRESSES


To the Members of the Symposium:

It is manifestly unnecessary for the members of this symposium to be reminded of the extraordinary importance of the subject matter for discussion here; nevertheless, it is useful to express the objectives to be sought in the joint examination of this topic at the present time. The Army being that part of the military forces of the nation primarily concerned with land operations, it is axiomatic that it should have as its goal means of land locomotion insensitive, as regards effectiveness, to topography, terrain types and climatic conditions. If it were possible to express attainment of this goal as a function of technical effort required, such a plot would undoubtedly exhibit an eventual asymptotic characteristic; however, intuitively we know that at present we are a long way from being on the asymptotic portion of the curve. Accordingly, it would seem that the objectives of this symposium would comprise at least the following:

- a. Promotion of professional interest in, and the expansion of acquaintance with, all important aspects of an urgent military requirement.
- b. Obtaining, through presentations and subsequent discussions, the benefit of the best scientific and technical competence as a guide for future activities.

It is hoped that the foregoing objectives may be attained by arrangement of the agenda in two parts. The first part of the symposium concerns vehicle mobility and deals with the question of soil properties and terrain types, especially in relation to trafficability, an aspect under the direct cognizance of the Corps of Engineers. The second part of the symposium is concerned with problems involved in the design of vehicles for cross-country locomotion with particular reference to meaningful design parameters which take adequate cognizance of the dynamics of soils under the impact of contact elements.

Eventual success in achieving the primary goal in the Army's land locomotion problem requires the wholehearted cooperation of every individual and agency that can contribute to its solution. Periodic stock-taking of the kind represented by this symposium should prove exceptionally useful to attaining this essential desideratum.


P. N. GILLON
Colonel, Ord Corps
Commanding

To the Members of the Symposium:

It is a matter of great satisfaction to the Office of Ordnance Research to be of service to the Corps of Engineers, the Transportation Corps, and the Ordnance Corps by making arrangements for this Symposium. The ever increasing tempo of scientific and technological advance permeates the whole structure of our society and the Defense Department is no exception.

The fundamental basic research on which all further development rests must be pursued at an ever increasing pace if our country expects to maintain its position in the forefront of scientific research. Equally important is the dissemination of this acquired knowledge to those groups who expect to use this newly developed information. An excellent way to maintain liaison among all interested parties, engineers and industrialists, university men and Defense Department scientists and engineers is the type of symposium described in the following pages.

The Office of Ordnance Research considers it an honor to conduct this conference for the services of the U. S. Army mentioned above.

Geo Glockler

GEORGE GLOCKLER
Chief Scientist

Program

**Interservice Vehicle Mobility Symposium
(Unclassified)**

**Stevens Institute of Technology, Hoboken, New Jersey
Auditorium, Building 1, Administration Building**

18-20 April 1955

Monday Morning

**Colonel P.N. Gillon, Commanding Officer, Office of Ordnance
Research, presiding**

Introduction

- 9:30 - 10:00** "Remarks of Welcome" - President F. H. Davis, Stevens
Institute of Technology
- "The Importance of Mobility to the Department of Defense" -
Major General Leslie E. Simon, Assistant Chief of
Ordnance for Research and Development
- 10:00 - 10:30** "Summary of Work on Vehicle Mobility in the United King-
dom", Mr. F. Usselman, The Fighting Vehicle Research
and Development Establishments of the British Ministry
of Supply. (30 minutes)
- 10:30 - 11:00** "A Review of the Corps of Engineers Trafficability Program
in Soils and Snow," Mr. C. R. Foster, Corps of Engineers.
(30 minutes)
- 11:00 - 11:10** Break
- 11:10 - 11:40** "Transportation Corps Requirements of Mobility," Mr. H. P.
Simon, Transportation Corps. (30 minutes)

Theoretical Topics

- 11:40 - 12:15 "A System of Physical and Geometrical Soil Values for the Determination of Soil Trafficability and Vehicle Performance," Colonel M. G. Bekker, Detroit Arsenal. (25 minutes)
- 12:45 - 1:45 Luncheon - Castle Stevens

Monday Afternoon

Carroll Dunn, Colonel, Corps of Engineers, Director Waterways Experimental Station, Corps of Engineers, Vicksburg, Mississippi, presiding

- 2:00 - 2:30 "Application of Recent Developments in Visco-Elasticity to Problems of Soil Mechanics," Professor E. H. Lee, Brown University (30 minutes).
- 2:30 - 2:50 "Dimensional Analysis and Scale-Model Testing in Mobility Research," Mr. C. J. Nuttall of Wilson Nuttall, Raimond Engineers, Inc., Chestertown, Maryland and Dr. J. P. Finelli, Stevens Institute of Technology (20 minutes).
- 2:50 - 3:15 "Methods of Evaluating the Effects of Terrain Geometry on Vehicle Mobility," I. J. Sattinger, University of Michigan (25 minutes)
- 3:15 - 3:30 Break

Practical Problems

- 3:30 - 4:00 "Development of New Track Concepts by the Ordnance Corps," Colonel G. T. Peterson, Detroit Arsenal. (30 minutes)
- 4:00 - 4:25 "A Radical Improvement in the Design of Tracked Vehicles," Mr. J. R. Doyle, Oliver Corporation, Cleveland. (25 minutes)
- 5:00 - 6:30 Social Hour - Castle Stevens
- 6:30 Dinner - Castle Stevens
Afterdinner Address: "Practical Approach to Research in Industry," Mr. Carl L. Hecker, First Vice President, Oliver Corporation, Chicago

Tuesday Morning

Mr. H. P. Simon, Transportation Corps, presiding

Practical Problems (cont'd.)

- 9:30 - 9:50 "Effects of Power Plants upon Mobility," Dr. E. T. Vincent, University of Michigan. (20 minutes)
- 9:50 - 10:15 "Analysis of Highly Variable Torque Power Plants for Cross Country Vehicles," Dr. W. I. E. Kamm, Stevens Institute of Technology (25 minutes)
- 10:15 - 10:35 "Field Mobility Testing," Mr. C. W. Wilson of Wilson, Nuttall, Raimond Engineers, Inc., Chestertown, Maryland. (20 minutes)
- 10:35 - 11:00 "The Performance of Tracked and Wheeled Vehicles in Snow," Mr. J. G. Thomson, Canadian Defense Research Board. (25 minutes)
- 11:00 - 11:10 Break
- 11:10 - 11:40 "Mobility Problems of the Navy in the Arctic," Mr. John T. Tucker, U. S. Naval Engineering, Port Hueneme, California. (30 minutes)
- 11:40 - 12:00 "Review of Corps of Engineers-Air Force Studies of Flotation Landing Gear," Mr. J. P. Sale, Corps of Engineers, Ohio River Division Laboratories. (20 minutes)
- 12:00 - 12:30 "Mobility Improvement for USAF Aircraft and Missiles Ground Support Equipment," Lt. J. H. Frye, Equipment Laboratory, Wright Air Development Center. (30 minutes)
- 12:45 - 1:45 Luncheon - Castle Stevens

Tuesday Afternoon

Dr. E. H. Bramhall, Office Chief of Ordnance, presiding

Practical Problems (cont'd.)

- 2:00 - 2:30 "New Methods of Tire Evaluation," Mr. Willard D. England, Detroit Arsenal. (30 minutes)

- 2:30 - 3:00 "Aerial Cone Penetrometers, Their Advantages and Limitations," Dr. A. A. Warlam, Consultant, Waterways Experiment Station, Vicksburg, Mississippi. (30 minutes)
- 3:00 - 3:15 Break
- 3:15 - 3:45 "Vehicle Design Concepts Most Adaptable to Highway Bridges," Mr. E. L. Erickson, Bureau of Public Roads. (30 minutes)
- 3:45 - 4:15 "Vehicle Design Concepts Most Adaptable to Highway Pavements," Mr. F. Burggraf, Highway Research Board. (30 minutes)

Wednesday Morning

Dr. George Glockler, Office of Ordnance Research, presiding

Environmental Studies

- 9:30 - 10:00 "Shore Trafficability Related to Environment," Mr. R. L. Wiegel, University of California. (30 minutes)
- 10:00 - 10:30 "Effect of Geological and Geographic Factors on Soil Trafficability," Dr. P.D. Trask, University of California. (30 minutes)
- 10:30 - 10:40 Break

General Problems

- 10:40 - 11:00 "Curriculum of Automotive Engineering," Dr. E.T. Vincent, University of Michigan. (20 minutes)
- 11:00 - 11:20 "Common Technical Interest of Various Agencies in Vehicle Mobility under Adverse Soil Conditions," Lt. Colonel L.S. Nelson, Detroit Arsenal. (20 minutes)
- 11:20 - 12:20 "Summary of Symposium," Colonel M. G. Bekker, Detroit Arsenal and Plenary Session.
- 12:45 - 1:45 Luncheon - Castle Stevens
- 2:00 - 4:00 Visit to Stevens Institute Laboratories.
Dr. Hugh MacDonald, Stevens Institute of Technology.

POST-SYMPOSIUM REFLECTIONS

Lt. Col. M. G. Bekker

This is the first time that the Office of Ordnance Research has sponsored an Inter-Service Symposium on Vehicle Mobility. Such a symposium and similar meetings were held almost periodically since 1943 when the problem was first recognized, under the auspices of several other agencies. The present interest of the Office of Ordnance Research in this field of research is the outcome of the intensified emphasis by the Ordnance Corps upon the development of more mobile vehicles, stemming from the requirements of modern warfare; which resulted in the establishment, for that purpose, of the Land Locomotion Research Laboratory at Detroit Arsenal.

Although one of the main purposes of this Symposium was to discuss the problems related to mobility and to the exchange of ideas in the broadest possible circles among those concerned with the problems, this Office, in order to stimulate further progress, has also attempted to find an answer at this Symposium to the more general question as to our present status and our next move in this vital field.

To achieve that goal speakers, invited from all the agencies which ever had anything to do with the discussed problems and discussions, were encouraged to disclose the strength and weakness of our present position.

The gratifying response to the invitation and the large attendance at the Symposium held at the Stevens Institute of Technology, inspire the confidence that no important segment of this work was omitted and that a true cross-section of the present "state of art" has been represented. If this assumption is correct, it would be logical to attempt an analysis of the discussions held and to draw some constructive conclusions which would guide further work.

The first, perhaps most impressive, observation which one could have made at the Symposium was the broadness and complexity of the problem of mobility in land locomotion. There appears to be little doubt that while the problems of mobility were discussed, two distinct phases of work linked together through a third phase have been found necessary: 1) a study of the applied mechanics of vehicle locomotion in a physically defined medium 2) a study of the real environment of locomotion which includes not only soil sciences but also geography, geology, meteorology, etc. 3) an operational analysis of vehicle values and environment values arrived at through research on phases one and two, which would provide the optimum practical solution of a given locomotion problem.

The Symposium was a success in clearly outlining this rather complex picture and in demonstrating a variety of theoretical and empirical

Post-Symposium Reflections (cont)

approaches, among which the paramount necessity for institution of a new type of applied mechanics was stressed, directly or indirectly, by various speakers.

Without minimizing the importance of empirical studies and particularly those theoretical deliberations which spearhead modern scientific development, it appears that the establishment of a package of knowledge which has been termed the applied mechanics of land locomotion is indispensable to further motor vehicle development in the same sense in which aerodynamic and hydrodynamics aided the development of an airplane and of a ship. Without such development all other studies will remain unrelated and haphazard ventures deprived of the benefit of generalization, so necessary in any broad treatment of the problem.

Obviously, such a task cannot be solved in its entirety by an individual, or a single group. The assignment of a mission and funds is not enough; this is not the way in which Von Karman and his students in the early nineteen twenties laid the foundation of modern aerodynamic research. Undoubtedly, their problems were somewhat different from those we face in land locomotion today, but methodologically the similarity appears perfect.

Thus, one conclusion which one may draw from this Symposium seems inevitable: the problem of research on land mobility will be handicapped as long as there is no professional group of career men and women to do the job on a full-time professional basis. This condition has never been satisfied before.

Mobility and trafficability until recently were treated as a number of "projects" to be assigned to a number of individuals, or organizations.

Since the problems involved are of a new and unprecedented nature, the individuals and organizations approached are necessarily experts in fields other than the applied mechanics of land locomotion, or application of geology or geography to the locomotion problems of wheeled and tracked vehicles. Moreover, there has been practically no operational research on mobility since there was little physical data available which an operations analyst could put into his equations and "gaming" assumption.

Thus, the work was not treated in a fully professional way. It was a sideline of other main activities, which ceased to interest its students once a "project" was closed.

The results of such a state of affairs were noticeable at the Symposium. Among the twenty-five documents presented only two or perhaps three papers have proposed new research concepts and/or practical application ideas. The others were, generally speaking, repeating and re-emphasizing thoughts which have been expressed five or seven years ago at previous symposia.

Post-Symposium Reflections (cont)

An explanation of this disconcerting situation would appear simple; there have been only a few, full time, professional individuals in this group who have made a career out of mobility research. These have been employed in this work since the latter part of the last war, within that period only one addition to these professionals has been made.

Everyone else participating in this Symposium seems to have been connected with this work on a part-time basis or through a casual rather than professional interest. The chief concern and main professional effort of most people as related to these problems have been concentrated in other fields than mobility. Should we then wonder that the Symposium also has revealed an intellectual stalemate which has paralyzed this work for the last ten years?

It would be unreasonable to expect that such a tremendous task as depicted by the Symposium could be solved by a few professional people. An influx of new talent and more career men and women thus appear necessary to provide for the survival of our activities.

As the engineers already successfully established in other fields of engineering apparently have not provided new cadres of research workers in this new field, the need for appropriate training and indoctrination of young engineers appears inevitable.

Only in this way can a new professional group be established. The Office of Ordnance Research agrees with the discussions held at this Symposium that a fairly large number of such professionals, perhaps a few hundred, could be absorbed by the industries and armed forces, if the approach to the problems of mobility as discussed at this Symposium is properly recognized.

With this thought in mind the Office welcomes a proposal by the University of Michigan, made at the Symposium through Professor Vincent, that a new type of a curriculum for automotive engineers be established, which would consider the modern methods of mobility study. This plan is being given serious consideration with the purpose of determining the nature of the support which may be needed for its implementation.

If this proposal results in a definite program and academic activity, the Symposium may be considered one of the most successful and important ever held.

CLOSING REMARKS

R. J. Jackson

All of us, I am sure, are grateful to Dr. Glocker and our other friends in OCR and to our host, Stevens Institute, for their labors in making this symposium possible.

Col. Bekker and others have pointed out the need for basic soil strength constants. Prof. Lee has presented a suggested theory for dealing with soil mechanics problems that more closely approaches the known load-deformation characteristics than the theory of elasticity. It is encouraging that such bold thinking has been brought to the attention of the attendants at the Symposium.

Mr. Wilson, Col. Brice and others have made strong recommendations for standardized methods of conducting field evaluation trials. This is indeed an encouraging trend. However, two words of caution are suggested: First, the concept of standard procedures should not be carried to the point where money is spent on collecting data that may never be used, and; Second, soil testing should be made to show the actual strength of the soil on which the vehicle operated.

Mr. Wiegel and Dr. Trask have demonstrated ably how a knowledge of how soil was formed can aid in obtaining quickly a picture of the general soil conditions in a given area and estimates of the soil strength. This is useful information when estimates are to be made by remote means. It is also valuable information if actual strength tests are planned because it permits intelligent location of the tests so that the maximum information can be obtained with a minimum of effort.

Col. Nelson, in his paper, emphasized the significance of soils in the mobility problems. You may be interested to know that proper recognition is being given to this aspect of the problem. It was in recognition of this fact that the Office Chief of Staff, Department of the Army has established The Mobility Research Center at the Waterways Experiment Station at Vicksburg.

The program presented here has been both interesting and challenging. Interesting from the standpoint of the variety of facets which the problem of vehicle mobility must include and challenging from the demonstration of how much there is to be done before we can hope to achieve the mobility which is so necessary to cope with the problems of military operations in this atomic age.

All this serves to emphasize the fact that the solution of the problems of mobility will require the united efforts of the best talents of those engaged in the fields which have been represented here during the course of this symposium.

CLOSING REMARKS

Colonel M. R. Brice

From the Transportation Corps standpoint, this meeting has been very enlightening in the presentation of the current approaches being taken by various agencies in arriving at their objectives. From these various approaches several points are evident.

One is the procedures being taken to solve problems peculiar to each agency and the resultant items. Many of these approaches are all from the empirical and are not supported by the means and methods of applied science. Indications from some of the papers presented show means of arriving at a conclusive answer by a scientific approach. However, these papers are definitely in a minority. The development of an applied science should be fully supported, for without full support and coordinated efforts in this direction by all services, we will still be bound by the expensive and time consuming empirical approach. Providing the vehicle designers with the necessary tools to accurately relate design to performance in the environment will enable the designers to utilize technical improvements and evaluate potential designs.

Another point in evidence in the discussion of this symposium are the areas in which action can be taken immediately to provide a better universal understanding of present methods of evaluation or analysis and provide basic data for use in the over-all objective of providing a usable science of land locomotion.

Solutions to the over-all problem appear to be in the provision of a larger source of specialized personnel in this field, better common understanding of the objective and problems concerned in establishing this applied science, and at all times a coordinating effort in approaching our goal.

On behalf of the members of the Transportation Corps who attended your symposium, we wish to express our thanks to the Office of the Ordnance Research for the opportunity to participate in this discussion.

CLOSING REMARKS

Lt. Col. M. G. Bekker

Mr. Chairman, Ladies and Gentlemen:

It is a great honor and privilege to be asked to summarize this symposium and I have accepted it with the humble resolution to do my best and also with hesitation for fear that I may fail to perform this task in a satisfactory manner.

A summary of the wealth of thought which generated this Symposium would be difficult to make even for those who have a better knowledge of the problems involved and better command of speech than I have. I sincerely hope that these circumstances will excuse any omission, or misrepresentation which may inadvertently occur in my review of our deliberations.

It seems to me that you may expect more than a mere summation of what has been said at the Symposium. If this is correct, I would like to take the liberty of giving you not an abstract but some kind of synthesis and general review of the problems of Land Mobility, as presented by various speakers and as viewed through the eyes of an observer who, like any of you ladies and gentlemen, would like to have a clear picture of the subject.

The title of the Symposium refers to the study of mobility. Practically every speaker has mentioned that word but it was not mobility which appears to have been the theme in our discussions. Actually I would say this was a confusing item, for no definition of mobility was given although many attempts were made to describe it in various terms.

What appeared most essential was a specific discussion on two distinct items; one, a vehicle and two, the environment of its operation. The vehicle was approached through the engineering sciences and a consideration of test development problems, whereas the environment was treated in the broadest sense of this word, wherein not only soil science, but geography, geology and meteorology were included.

I think everyone will agree with me when I say that both the students of the vehicle and the students of the environment have attempted in their discussions to arrive at some system of physical values which would provide an optimum solution to the locomotion problem in the assumed physical environment.

However, it was mentioned that the solution of this problem will not suffice to provide final answers in which over-all economy and effectiveness are expected from a broad operational point of view.

Although there was no paper presented at this symposium on the operational research of mobility, because of circumstances beyond control, the role of this discipline in the solution of mobility problems seems to have been well established.

With this background, which appears to be the very foundation of the study of mobility, the details of discussions held at this symposium may be reviewed with greater clarity and more understanding.

To start such a review chronologically, I will first mention that the absence of the British paper prevents me from dwelling on their subject at this moment. I will therefore start with the excellent presentation by Messrs Foster and Mellinger who have shown two different empirical methods, both of which have been successfully applied in predicting certain aspects of soil trafficability as related to motor vehicles and landing gears of airplanes: the Waterways Experimental Station in Vicksburg has employed for this purpose the cone penetrometer index of especially remolded soils whereas the Ohio River Division Laboratories applied such more generally used measures as "subgrade modulus" and the CBR.

This may have suggested the desirability of a more unified approach to the problem of soil-vehicle relationship and stressed the necessity for development of a scientific method which would parallel the empirical approach. The paper by Professor Lee has shown how much may be expected theoretically in this field while the paper by Mr. Nuttall on dimensional analysis, despite the cautiousness of its writer, suggests another avenue of approach. My own presentation, if I may mention it at all, has attempted to establish an engineering approach which would be compatible with the general methods of applied mechanics, and which would satisfy the designer and user of a motor vehicle.

It would appear that the papers by Messrs Simon and England have explained primarily the necessity for this kind of approach. The lack of knowledge in the field of applied mechanics which would enable one to properly evaluate a wheel seems to have led to the development of extremes: giant 10 foot tires on one hand and small-diameter rubber cylinders on the other. Usually, extremes will not satisfy an average and some one must find a middle course. This appears impossible if physical research is not backed by operational research.

In these and similar problems the decisive factor is not only the physics of the environment, but also the geometry of the ground surface. Mr. Sattinger spoke about modern computing methods which make the task of evaluating terrain roughness quite feasible, and which solve the previously unsolvable problems of vehicle vibrations. Caution has been voiced, however against an introduction of too much detail, which may lead to interesting solution but of little practical value.

The review of theoretical studies was followed by a review of practical solutions. Colonel Petersen has shown how the research work so far performed by the Ordnance Corps helped the many attempts which were aimed at a design of more mobile vehicles. His remarks have re-emphasized that "a thorough knowledge of a new type of applied mechanics as related to vehicle performance is necessary in order to develop optimum mobility in various soils".

1

Mr. Doyle described new concepts in vehicle design which were originated in a research rather than development activity and his comments left very little doubt that commercial development of motor vehicles may gain much from the development of military vehicles, and vice versa.

The paper by Professor Vincent suggests that future vehicle development depends more on the volume of the engine block than on engine weight. This indicates again that a morphological change in vehicle design may mean more to future progress than merely the technological improvement of an engine or transmission.

A bold approach in a search for new concepts of locomotion was presented in the paper by Professor Kamm; the dynamic lift track, proposed by Dr. Kamm, would require the development of new power plants to provide constant power operation instead of the presently available constant torque operation. This illustrates the magnitude of the problems which face automotive engineers if we want to depart from conventional solutions.

To answer all pertinent questions, appropriate test data must be made available. Mr. Wilson spoke on this subject and illustrated the existing difficulties. There has never been a doubt that there is much need for clarification of definitions and test methods in order to arrive at more reliable and comparable conclusions. This, however, cannot be done through a mere standardization of conventional methods. Undoubtedly, progress depends more on the establishment of new methods rather than on the preservation of the status quo.

Mr. Thomson reported data on snow tests performed under conventional methods and presented a number of design characteristics which leads to the rather optimistic conclusion that the problem of over-snow mobility in the Arctic is practically non-existent. This conclusion is not, however, confirmed according to the other papers and particularly that by Mr. Tucker who stressed the fact that today only a sled train moving at 2 mph is available for Arctic use. Attempts of the Transportation Corps as described by Mr. Simon illustrate the same situation.

The core of the problem seems to be the requirement that an Arctic vehicle must not only operate economically on snow but also on marshy terrain as encountered during the summer months. This is why the use of conventional concepts and vehicle elements does not satisfy such extreme conditions. The need for new ideas appears to have been well demonstrated.

Actually this problem is not unique and is not restricted to cross-country locomotion. Messrs Burgraff and Erickson have shown in their papers the magnitude of the problems they face in a search for designs which would satisfy highway operations.

Obviously, cross-country operations involve many more problems, and the study of such vehicle locomotion environment presents a wide open field, as was evidenced in the papers read by Dr. Wiegel and Dr. Trask.

On the basis of what has been discussed in this symposium, there appears to be little doubt that a study of the relationship between a vehicle and the environment of its operation is a relatively new venture; it is, indeed, an almost entirely new aspect of automotive engineering. Professor Vincent is beyond all doubt in agreement with this statement as he has considered a possible re-adjustment of the curriculum in automotive engineering at his university. This re-adjustment would include those subjects which have not been taught or not stressed enough in present automotive engineering training.

The training of professionals appeared to be the crux of the whole problem. If we agree with Colonels Gillon and Register, and Dr. Glockler that the discussed work is of utmost importance, and with Colonel Petersen that there is an urgent need for the establishment of a new kind of applied mechanics which would contribute to vehicle mobility in a manner similar to that in which aero-and hydrodynamics have contributed to the progress in aviation and naval architecture, then the proposal by Professor Vincent cannot be more timely, and in my opinion, relates not only to military but also to civilian students. For there is no better opportunity of achieving success in this new complex field than to provide new talents and vision through appropriate training and indoctrination of engineers. This is actually what President Davis said in his opening remarks.

The present difficulty in finding new workers is very serious. Colonel Nelson, describing the mission and activity of the newly established Land Locomotion Research Laboratory at Detroit Arsenal, has stressed the problem of manpower: it is almost impossible to find personnel with interests and educational background which could properly aid the research in vehicle mobility. I would venture to say that the industries must be facing exactly the same problem. Thus, whatever else we may consider, we must all agree that the human element is the pivot around which future progress must revolve. In my . . . work on vehicle mobility, this has always been a major problem.

The need for a new look has been stressed at the symposium, but occasionally not without a nostalgic glance at the past, I believe this is not worthwhile. Today, we face an entirely different world and a new challenge within a new field. As in any venture, the success in research on vehicle mobility depends on the man who would dedicate himself to this task rather than who would treat it as an interesting sideline.

The complexity of this work and its vastness both in scope and volume indicates that only a long range permanent activity may bring the desired solutions. As the need for a full pledged professional approach thus appears to have been established, I would like to close this summary with the quotation from Dean Doan of the Ohio State University which I have borrowed from the admirable and inspiring speech delivered Monday evening by Mr. Hecker: "The first need in America today is a new generation of trained men and women who can do those things which have never been done before...leaders in thought and deed, not in routine and tradition... where are we to look for these (people) if not from our universities....?"

ADDRESS

PRACTICAL APPROACH TO RESEARCH IN INDUSTRY

Carl L. Hecker

MR. TOASTMASTER, MEMBERS OF THE SYMPOSIUM ON VEHICLE MOBILITY, HONORED GUESTS:

I am deeply indebted to Colonel Bekker, George Glockler, and your group for your kind invitation to address you here tonight. At the outset, let me say that our country is extremely fortunate that we have a far seeing Ordnance Research Organization which is working diligently to make America strong so we can, in the language of that great American, Theodore Roosevelt, "Speak softly and carry a big stick."

I am greatly moved by the exalting introduction of your toastmaster. It calls to mind a quip related to me by one of my associates recently. His young 10-year old son came home from school and I believe was secretly trying to depress his Dad's ego when he related, "Dad, have you heard the latest Beatitude?" When his Dad fell for the question, he answered, "Blessed are they who go around in circles, for they shall be known as big wheels."

Despite the fact that I was somewhat awe-stricken by the voluminous report and summary of the transactions of your Symposium, secretly I feel somewhat at home here tonight on the campus of this great educational institution for two reasons.

First, its President too is a fellow alumnus of my Alma Mater, Ohio State, and whenever we Ohio Staters get together we have much to talk about and second, I regard Hoboken as my second birthplace in this great country, for while it was in Columbus, Ohio, that I was born, my Father came here to this city as an immigrant from his native land some 66 years ago. For me that was a very fortunate circumstance, for this is the most wonderful country in the world, and all of our energies, both mental and physical, should be directed toward keeping it so strong that our enemies dare not attack us from without, while at the same time we cope with those within our borders who might destroy us.

Within my lifetime I have seen and had some part in two major wars and a third, which some call a policing action, but which, when measured by the scope of previous wars in our history, easily could have been called a third. I believe most military experts will agree, and certainly in the case of World War II that many of the decisive battles were fought and won on the production lines of American industry. Research and industry can win wars and it can also provide a better way of life, a higher standard of living for all. I would be sadly remiss as an American corporate official if I did not take this opportunity to comment briefly on the subject of "Automation," which is under a great deal of discussion in America today. There are those in this country who are preaching a philosophy that improved technology, the application of automatic

ADDRESS (cont)

machinery, the development of a system for eliminating physical effort and fatigue from manual operations shortly will displace millions of American workers, destroy our high standard of living, and reduce people to dole subsistence. That type of thinking at the outset of the industrial revolution in England, and in the feudal ages, is easily comprehensible but today we have only to look at our great industries in which some form of automation has already been applied to appreciate the fact that machines make jobs, lower the cost of production, increase the purchasing power of our people, and create greater employment for all. Automation is merely the result of the application of research to a study of the elimination of manual effort, fatigue, and hazard factors in industry.

I want to talk to you a little while tonight about a practical approach to research in industry. When I speak of industry, I am not talking about a handful of great and wonderful American corporations which have gigantic institutions devoted solely to pure research, out of which have come great developments in atomic energy, nuclear physics, newly discovered elements and materials. I am not talking about the Fermis, the Edisons, the Einsteins, the Marconis, but I am talking about the average-sized American industry such as my own, which comprises the great majority of industry in our country. In passing, I decry the lack of original development within our own shores. Many of the original developments of the past 20 years have not been American. It is true that we have assisted in their development, but even much of that development came from our immigrant inventors and scientists who fled their native lands for various reasons.

That leads me to my first concept of an approach to a research program. Wonderful buildings, marvelous equipment, large amounts of capital, do not make a research program. The first requirement is people. I would like to quote Dean Doan of Ohio State, "The first need in America today is a new generation of trained men and women who can do those things which have never been done before -- leaders in thought and deed, not routine followers of tradition - men and women who are intellectually capable, morally responsible, emotionally and spiritually mature, socially competent, and last but not least, physically fit. Where are we to look for these well-rounded citizens of the world except from our universities where there remains, if anywhere, the essential opportunity to gain acquaintance with the best that men have said, and done, and dreamed -- and are now in process of saying and doing, and dreaming?"

How long will it take us to train a Fermi in one of our factories? It has been said that last year we produced only a handful of high school physics teachers in America. The training of future research scientists must be done in our colleges and universities. I am glad to see that American industry is awakening to the fact that it has a job to do in supporting, where necessary, those institutions of learning who find it

ADDRESS (cont)

impossible at least in the early stages of growth to be self-sufficient. In this development plan the small college has a very vital part to play. Nature does not say that all great scientists will graduate from Stevens Institute of Technology, Yale, Harvard, Michigan, or even Ohio State. I enjoy noting the scholastic background of many of the authors of the great developments in science today. Many of them put their Alma Maters on the map, for they were never heard of before the discoveries of their alumni.

At long last our engineers and our scientists are being given the recognition which they so richly deserve in America. In the old world they have had that recognition for centuries. Very few of our average citizens appreciate fully the sacrifices and hard work required to produce an outstanding development in science and engineering today. An engineer and scientist have their days and moments of exasperation before they achieve final success.

I am reminded of a story I heard recently. A young husband, Paul Smith, came home from work to find his wife in tears. Upon questioning her she replied, "I demand an apology from that boorish druggist friend of yours, Bob Jones. I never was so humiliated and insulted before in my life. You go right down there and get it straightened out immediately." Now, Paul was the conciliating type and so he tried to get the facts to which she replied, "It is too terrible and humiliating to repeat, but you go down there instantly and get that apology." Paul saw there would be no peace in the family unless he complied, so reluctantly he left to see Bob the druggist. Bob greeted him warmly as if nothing had happened and Paul informed him that his wife demanded an apology. "Apology for What?" asked Bob. "Did you see or talk to my wife today?" asked Paul. "Oh, that," said Bob. "Well let me tell you. Suppose that you overslept in the morning and when you got up your wife asked if you'd mind getting your own breakfast. You went down and looked in the refrigerator and no eggs. There were only two slices of bread which you put in the toaster while you were making coffee, and these burned to a crisp. You went out and got into your car and after a block you ran out of gas. You shoved the car to the side of the road and walked the rest of the way to work only to find when you arrive at the store that you'd left your keys at home. You ran back home and finally returned to the store to find a dozen customers at the door, each one wanting to be waited on first. When you got into the store the telephone was jangling madly. Finally you could stand it no longer, and in desperation went over and took down the receiver. What would you say if you heard a voice at the other end of the line say, 'How do you use a thermometer?'" Well, that is a typical day in some of our engineering and scientific lives.

There is a growing emphasis today upon the need for a high degree of morale and esprit de corps in all departments of business. My prediction is that our enemies with their way of life will never achieve the results

ADDRESS (cont)

which we are securing and will secure with their regimented science and industry. Let me illustrate it with a story which I heard years ago and have repeated many times.

Many years ago in the city of London, England, there was a great art exhibit of the paintings of that day. All of the critics came to scoff as well as to praise. Among the paintings prominently displayed was the English masterpiece by the great painter, Holman Hunt. I am sure many of you are familiar with this work entitled "The Master." Hunt was more than a great painter, he was a keen judge of human nature and he came expressly to hear the comments. Presently he heard a voice say, "Why, the painting isn't finished." "Why do you say that, my friend?" asked Hunt. "Well, can't you see that there is no handle on the door on which he is knocking," answered the critic. "My friend," said Hunt, "That door on which the Master is knocking is no ordinary door. It is the human heart. It needs no handle, for it can only be opened from within." I am very hopeful that our enemies will continue to follow the policies which they are following. Only free men will ultimately achieve success in the development of science and industry in the world in which we live.

I have hinted at the fact that it is my belief that the field of fundamental research should be left to our great educational institutions. Applied research belongs to industry. Now I would like to comment briefly on the organization of our research and engineering departments in industry. In order to achieve maximum results and effectiveness, I believe we should practice a program of decentralization. This applies whether an industry is of a single or plant or of a multi-plant organization. Permit me to illustrate by a brief account of what my own company accomplished during the Korean emergency. Ours is not a large company, as measured by some standards, and yet during this emergency in addition to our long line of civilian products, we produced for Ordnance the following: Aircraft - complete center fuselage sections for the B47 for Boeing; Ammunition - 60 MM cold extruded shells, 155 MM hot forged shells; Weapons - the 155 MM gun carriage, the 81 MM mortar, the 105 & 106 MM recoilless rifle and mount, the 76 MM recoilless rifle; and Automotive - final drives for the medium tank, oil coolant fans for the Continental engine for the medium tanks, and several research and development contracts such as the one which is mentioned in this Symposium.

By decentralization of engineering and research organizations, the total result accomplished is greater than would be accomplished if the organization were all concentrated together. More men of stature are developed, time is saved as well as money.

Now I'd like to comment briefly on forward planning. World competition today is so keen, whether it be in a civilian product or a military product, that only by the most searching gaze into the future, the most careful consideration of future needs is it possible to

ADDRESS (cont)

determine the specific program of research and engineering development. Several times during the past year I have been approached by private research organizations requesting assignments. My specific answer to one and all is to state that we need no help in carrying out the specific details of a program but we need help in formulating what the objective or what the program itself will be. I believe the outstanding success of some of our great American researchers such as C. F. Kettering of General Motors lies not in their scientific mind for working out the details of a program, but in their recognition of a need for the program itself. This is one of the great problems of industry, and it can be nurtured by the fundamental research programs of our great universities and educational institutions.

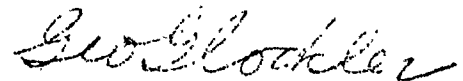
In considering this overall research program in America today, I hope that we never again will experience the hesitancy which some of our scientists displayed when they considered the moral wrong or right of a research program. Down through the years, ringing in my own ears over and over again, I have heard the words of that great American, "My country, may she ever be right. But right or wrong, my country."

Thank you for your kind attention.

CLOSING REMARKS

The Office of Ordnance Research wishes to express sincere thanks to all who attended this Symposium in a splendid effort of cooperation. It has been a successful and illuminating venture. I believe we have now a clear-cut picture of where we are and where we should go in the future.

The Office of Ordnance Research indorses the remarks by Colonel Bekker made in his Post-Symposium Reflections and agrees that the future success of work on Mobility in Land Locomotion depends on the establishment of a fully professional activity. We welcome the interest expressed by the representatives of our universities and hope that they will help the establishment of a professional cadre of researchers. The Office of Ordnance Research will cooperate in this task to the fullest possible extent.



GEORGE GLOCKLER
Chief Scientist
Office of Ordnance Research

PART TWO

ABSTRACTS AND DISCUSSIONS

SUMMARY OF WORK ON VEHICLE MOBILITY
IN THE UNITED KINGDOM

F. L. Uffelmann

This paper was not presented at the Symposium due to the absence of Mr. Uffelmann.

Abstract

Items of research carried out in the U. K. since 1945 are described. They include the theory of tracked vehicle sinkage developed by A.O.R.G. as a means of forecasting mobility from vehicle characteristics and soil data and the simpler-to-use formula suggested by Evans in 1953. The vane penetrometer is mentioned as a useful instrument for field use.

Other items mentioned are F.V.R.D.E.'s full scale soft ground trials with Comet and theories of tracked vehicle performance; laboratory investigations into the sinkage of plane footings, wheels and probes, and of the rolling resistance of wheels on soft ground; the measurement of stress in the ground beneath tracked vehicles.

A REVIEW OF SOIL AND SNOW TRAFFICABILITY

C. R. Foster and S. J. Knight

Abstract

The Waterways Experiment Station, Vicksburg, Mississippi, is studying the trafficability of soil and snow under Corps of Engineers' Project 8-70-05-001, "Trafficability of Soils as Related to the Mobility of Military Vehicles." This project includes two phases of development:

Phase 1 - development of instruments and techniques for measuring trafficability by contact means.

Phase 2 - development of methods for estimating trafficability without contact.

Cone index, a measurement with an instrument called the cone penetrometer giving an index to shear strength, has been correlated with the performance of military self-propelled and towed vehicles by actual tests in thoroughly mixed and uniformly wetted fine-grained soils 4 ft. deep. Subsequent tests on natural (in situ) fine-grained soils revealed the necessity for a test for anticipating changes in soil strength occasioned by vehicle traffic. A test was developed which produces a quantity, remolding index. Cone index and remolding index together can be correlated with vehicle performance in natural fine-grained soils.

Systems for classifying vehicles and soils from the trafficability standpoint have been developed. Charts are available for estimating slope-climbing ability, towing ability, and towing force required in fine-grained soils when cone index and remolding index are known.

A catalogue of airphoto patterns and corresponding seasonal trafficability data for the estimation of trafficability of sites for which airphotos are available is in the process of preparation. Considerable data are now available. Studies continue to correlate weather with trafficability so that the trafficability of inaccessible sites may be predicted based on knowledge of soil types and weather conditions only. Important results from these studies are available at the present.

The trafficability of coarse-grained soils, particularly sand beaches, and snow is being studied. Initial results indicate that techniques of measurement similar to those used in fine-grained soils may also be employed in sand and snow.

Several trafficability maps have been prepared, and methods of improvement of mapping procedures are being studied.

COMMENTS BY M.G. BEKKER

1. Messrs Foster and Knight have made an excellent presentation of the pioneering work by the Corps of Engineers. The usefulness of this work in prediction of soil and snow trafficability has been well demonstrated with reference to existing vehicles.

From the procedure described by Mr. Foster it appears that 50 passes were selected as a criterion of vehicle failure to cross the given soil. That failure has been defined as bogging down of the vehicle due to compaction of soil which takes place during the repeated passes.

However, sinkage apart from soil properties depends on the thickness of compacted layer. In the tests conducted by Mr. Foster that layer was 4 feet deep.

It appears possible to assume that if that layer were, let us say 6 feet deep, compaction resistance which could immobilize a vehicle would occur later than after 50 passes: If the tested soil layer were thinner than 4 feet, it may be expected to occur sooner. Have these problems been investigated? Is the number of 50 passes representative of every vehicle in an average terrain?

This appears important as the bulb of pressure of a 2 foot wide track will extend approximately 2 feet in depth. But a heavy tractor like the Caterpillar D8 with extra wide tracks may extend the sizeable pressure beneath the tested 4 foot soil layer. Is the 50 pass number then valid?

2. In your paper, a formula for mobility index is proposed. That formula is composed of other indices like pressure factor, weight factor, track factor, grouser factor, etc. Thus, the actual definition of your mobility index depends on the definition of several other factors. How did you arrive at these definitions?

3. How has the graph, Fig. 2, been computed to relate "mobility index" to the "cone index?"

4. On page 7 Mr. Foster describes certain difficulties in correlating mobility and inflation pressure with the cone index. I would like to take this opportunity to show how this problem may be solved by means of certain approximate methods available in land locomotion mechanics so far developed.

It may be demonstrated that performance and inflation pressure can be linked together if certain soil values are available, so that an approximate equation compatible with any other solution of applied mechanics can be devised.

Evaluation of tire performance.

Assuming the following properties for sand $\phi = 35^\circ$; $n = 1$; $k_c = 0$, and $k_\phi = 3.5$. The rolling resistance of a rigid wheel (70 psi inflation) may be calculated by the formulae:

$$R_c = \frac{1}{(3-n) \frac{2n+2}{2n+1} (n+1) (k_c + b k_\phi)^{\frac{1}{2n+1}}} \left[\frac{3W}{\sqrt{D}} \right]^{\frac{2n+2}{2n+1}}$$

Where $b =$ max. width, inches
 $D =$ max. dia., inches
and $W =$ load

With a 11.00 X 20 Tire loaded to 6,000 lbs.

$$R_c = \frac{1}{2^{4/3} \times 2(41.3)^{1/3}} \left[\frac{18000}{\sqrt{43.2}} \right]^{4/3}$$

or $R_c = 2,240$ lbs

and $\frac{R_c}{W} = 0.373$

for load of the front wheel $W \approx 3,500$ lb; $\frac{R_c}{W} = 0.312$

Assuming that a 10.00 X 20 tire inflated to 10 psi has a contact area of length $L = 17$ inches, the motion resistance, calculated by the formula:

$$\frac{R_c}{W} = \frac{W^{1/n}}{(n+1)(k_c + b k_\phi)^{1/n} (L)^{\frac{n+1}{n}}} = \frac{6000}{2 \times 3.5 \times 10 \times (17)^2}$$

thus for $W = 6,000$ lbs;

$\frac{R_c}{W} = .346$

for front wheel load $W \approx 3,500$ lbs

$\frac{R_c}{W} = .173$

Gross traction in ordinary sand is determined by Coulomb's equation
 $T_g = \tan \phi$ and the available net traction (slope %) is:
Slope (%) = $T_{net} = (\tan \phi - R_c/W) 100\%$

Hence slope performance:

for 70 psi tire $.7002 - (.373 \times .312) = 1.5\%$

for 10 psi tire $.7002 - (.346 \times .173) = 18.1\%$

As we see the results are in accordance with experimental values quoted by Mr. Foster.

This is, of course, a crude illustration of the method, still not quite perfected.

It seems to show clearly, however, that a general approach consistent with other applied mechanics may be made successfully, without the help of empirical "factors".

REPLY TO M. G. BEKKER'S COMMENTS

Col. Bekker's first comment refers to depth of soil, its effect on number of passes of a vehicle, and raises the question of the validity of the 50-pass criterion used by the Waterways Experiment Station.

Concerning depth of soil in prepared-lanes testing, immobilization normally occurs soon after a vehicle begins to drag its undercarriage. The greatest clearance of any of the vehicles tested was 20 in., and the greatest track width was 28 in. Four feet of soil (as nearly consistent as to moisture and density as possible) was, therefore, considered sufficiently deep to test the ability of a vehicle to travel through it. A deeper test lane of the same soil would have had no appreciable effect on the vehicle's performance. A significantly shallower test lane, on the other hand, might have influenced the tests, not as Colonel Bekker suggests by causing an earlier immobilization but by permitting the vehicle to run indefinitely on the firm, unprepared surface.

It seems pertinent to mention that the cone index requirements quoted for a vehicle must be found in the layer at 6 to 12 in. below the soil surface (for most vehicles) and that cone indexes below 12 in. must be equal to or greater than those between 6 and 12 in.

The criterion "50 passes" is simply an arbitrary test condition. Requirements for one pass of a vehicle could have been developed in the same general way as were requirements for 50 passes, except that it is felt that the consistency or reproducibility of one-pass tests would not have been as good because of such influences as driver ability, small variations in soil conditions, small differences in speed of vehicle, mechanical condition of vehicle, etc.

It is possible that the heavy D8 tractor with extra wide tracks (especially if its clearance is high) would not show results as consistent as those for the other vehicles tested had it been tested in a pit only 4 ft. deep, because of the influence of the firm layer below 4 ft. However, it is our opinion that the differences in test results would have been too small to measure since, in the final analysis, it is the soil immediately surrounding the tracks that determines whether the vehicle will move after considerable rutting has occurred. The largest vehicle tested by the Waterways Experiment Station was a T92 mobile howitzer which weighed 124,700 lb, had tracks 28 in. wide and a clearance of 15 in.

In paragraph 2 of his comments, Col. Bekker asks how we arrived at definitions for the various factors used in the mobility index formula. The selection of the factors was on the basis of their observed importance in the tests in prepared lanes. Definitions of the factors was on the basis of logic, i.e., contact pressure is weight divided by area, deep grousers provide better traction (in most cases) than shallow grousers, etc. The numerical value of the factor was determined by many trials of the factors in various formulas for mobility index until a formula was found which produced mobility indexes which, when plotted against respective cone indexes (for the vehicle testes), yielded a reasonably smooth curve.

REPLY TO M. G. BEKKER'S COMMENTS (cont)

The question posed in paragraph 3 of Col. Bekker's comments is answered in the last sentence of the above paragraph.

It is gratifying to know that analytical methods exist for correlating vehicle performance and inflation pressures. We would certainly like to have more of such information presented by Col. Bekker, in more detail, for the purpose of comparing our field data.

TRANSPORTATION CORPS IN THE FIELD OF MOBILITY

H. P. Simon

Abstract

A historical summary covering the work accomplished by the Transportation Corps for the improvement of land transportation, required for negotiation of terrains generally categorized as arctic, desert and marshy. Summary includes a practical approach to providing high cargo capacity, high mobility equipment for the Transportation Corps in areas where road nets are not available. Indicates future work that will be accomplished and items of research that should be initiated immediately. The paper distinguishes between the Transportation Corps requirement for vehicles with high cargo capacity and mobility as compared to tactical needs for light weight, highly mobile and maneuverable vehicles.

Equipment and present method of operating over permanent snow areas is reviewed. Study and testing of large diameter, low pressure tires in a permanent snow area has resulted in a concept of a multiple trailer unit known as the "Snow-Train." This is a new approach to the mobility problem for mass transportation.

COMMENTS & QUESTIONS BY H.G. PEKKER

1. I would like to comment on the need for tire research which Mr. Simon has stressed so ably in his paper. The problem of the tire is not different from the problem of a track. Acutally, a tire produces a contact area and a track produces a contact area. The difference in loads which the given contact area can support does not lay in what is above that contact area but in the forces which act upon the soil. Thus, many factors listed by Mr. Simon, such as carcass thickness, number of plies, tread design, etc., enter in the considerations of soil-vehicle relationship as secondary factors, and I believe, should be separated from any work on the mechanics of a wheel as such.

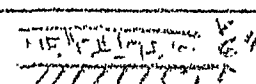
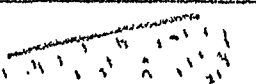
If we assume this attitude, then the problem of comparing duals, for instance, with single tires appears relatively simple. To this end Bernstein's equations for rigid wheels may be used if the inflation pressure is high enough.

If we do so, it will be found that the whole problem does not produce a "yes" or "no" solution but a number of conflicting answers. For instance, in one type of soil duals will be better; in another a single tire of the same overall load capacity will be better.

In general, there is no "yes" or "no", "go" or "no go" answer, in respect to any wheel problem. As I see it there will always be a number of conflicting factors in tire selection and it is up to Operations Research to resolve the conflicts in such a way that optimum over-all performance is obtained with the maximum probability.

To be more specific, let me use an example: by means of equations previously quoted we can determine the slope-climbing ability of various tires under consideration.

For instance:

Terrain Type	Tire		
	Regular 7.10x15	high flotation 9.00 x 20	Low Flotation 5.00 x 30
Mud 	4%	0	8%
Sand 	0	24%	1.5%

From this table it may be deduced that in sand the best performance is produced by a 9.00 x 20 tire. This tire, however, will stick in mud 3-4

inches deep. A similar, but reversed, conclusion may be drawn with reference to a 7.10 x 15 tire. But the over-all performance is best if we use a 5.00x30 tire.

Such tables may be computed for more terrain conditions than the two shown in this table. As the number of conflicting performance indices multiply only a theory of games may provide the best probability of success, and thus the best selection of a tire.

Incidentally the table shown here is known in the theory of games as a matrix, and forms a basis for a rational treatment of the problems. Those selecting a tire must play some kind of a game before they arrive at any conclusion: a scientific approach to gaming has already been made.

This fact although tacitly recognized has never been considered in a systematic, scientific way. Instead, many empirical formulae have claimed that they can provide a "quantitative" factor for tire selection. As I see it, these "factors" have lead us to follow not the golden rule of the middle road, but forced the development in the extremes: giant 10 foot tires on one hand and 2 foot rubber cylinders on the other.

2. Mr. Simon mentioned that the spaced link track is particularly applicable to light weight vehicles. This is basically true, but according to the available knowledge of the subject, I would like to add that this does not mean that the spaced link track is not applicable to heavy vehicles as needed, for instance, by the Transportation Corps.

To avoid any theoretical considerations, this statement may be amplified in the following way:

Take a spaced-link track and a conventional track, both having the same over-all dimensions. The spaced-link ground contact area will be covered 30% with steel or rubber plates and 70% will remain uncovered. The conventional track will cover the same space with 100% steel, or rubber plates.

If we measure the grip of both tracks with which they stick to the ground, it will be found that for certain loads the spaced-link track pulls more than the conventional one. For higher loads both tracks display the same gripping power, and for still higher ones, the conventional track is slightly superior than the spaced-link track; or for practical consideration the spaced-link track is equal to the conventional track.

However, at the same time, it will be found, in soft soils, that the motion resistance of the conventional track increases much faster with load and sinkage than that of the spaced-link track. For instance, it has been estimated during the tests made at Aberdeen Proving Ground that the spaced-link track in loose deep mud may encounter 4 times less motion resistance than a comparable conventional track.

Consequently, the drawbar-pull or slope climbing ability, which depends on the difference between the gripping power of the track and the

motion resistance is invariably higher at critical conditions for the spaced-link track than for a conventional track; this is true for all track loads.

Thus the spaced-link track appears suitable for all weight classes. The same may be paraphrased in a different way: it is a well-established fact that a 100% coverage of the ground contact area by a conventional track produces worse or, the same pulling power than a 30% coverage of that area by the spaced-link track. The question is then, why cover that area entirely? Why not keep it open, and let the dirt flow freely instead of bulldozing it at a tremendous expenditure of power and at the danger of down bogging?

The claim that the spaced-link track may sink deeper than a conventional one because of lack of flotation does not mean that it has more motion resistance: on the contrary, it has less.

It appears to be a mistake to compare the spaced-link track to the conventional track according to the sinkage criterion. A spaced-link track vehicle designed properly will sink approximately 40 inches and yet keep moving, whereas, a similar conventional vehicle will bog down at a sinkage of some 12-15 inches.

The degree of improvement through adoption of the spaced-link track depends on vehicle design and soil properties. It has been demonstrated theoretically and experimentally that a mere replacement of the conventional track with a spaced-link track will not result, for the most frequently encountered soil conditions, in much change in performance, if at all. Depending on vehicle type, it may even result in a deterioration of performance; this has very often been interpreted as a failure of the spaced-link track to improve traction and mobility.

Such a view, according to the available knowledge of the problem is incorrect and it seems imperative to recognize that the spaced-link track concept does not embrace the track alone, but also an appropriate design of the suspension system and of the whole vehicle. This subject will be discussed in the paper by Mr. Doyle of the Oliver Corporation which has acquired considerable experience in this new field of design.

3. The graph produced by Mr. Simon appears to indicate that there is not much difference in rolling resistance between a sled with plastic skis, and the LeTourneau trailer with 120.00" tires. Why then is there a need for the replacement of sleds with these gigantic tires in snow operations, if the cost difference between both contact media is considered? Would the author like to comment on this subject?

REPLY TO M. G. BEKKER'S COMMENTS

1. The comments offered by M. G. Bekker on the need for tire research is appreciated. This Command believes the analysis is well founded if we limit it to rigid wheels and high inflation pressure tires.

a. Bernstein's equations were adequately justified for towed rigid wheels by C. J. Nuttall in Stevens Institute Report No. 418, but even here the author indicated a need for further research to verify the equation for powered wheels.

b. In M. G. Bekker's report, ORO-T-247, low pressure tires are regarded as tracks since this Command believes the author could not adequately apply the form to Bernstein's equation.

c. Perhaps the factors of carcass thickness, number of plies, and tread design are secondary factors, when considering the soil-vehicle relationship, but in order to make a determination of the relationship of low pressure tires to soils, I repeat my original statement that quantitative data for tires (variable pressure) relating load, inflation pressure, diameter, cross-section configuration and life expectancy to terrain, is required to verify theoretical analysis and practical applications.

2. This Command concurs whole-heartedly in M. G. Bekker's statement on the space link track, and await Mr. Doyle's paper which it is hoped will aid in designing a high gross weight vehicle in the range of 30,000 to 50,000 lbs.

3. The graph presented in Mr. Simon's paper consisted of the only available data, at the time, on a comparison between a sled, tracked trailer and a large diameter wheeled trailer. Since the paper, an extensive test was performed at Houghton, Michigan on the T-79 Tracked Trailer, with a rated payload of $1\frac{1}{2}$ tons, a sled with a $7\frac{1}{2}$ ton payload, a wheeled trailer with 30x33 tires, and a 10 ton payload, and a wheeled trailer with a $33\frac{1}{2}$ x 60 tire (120" OD) and a 10 ton payload. The motion resistance for these vehicles in pounds per ton of payload was 1350, 260, 290 and 65 respectively. In addition, starting drawbar for the 120" O.D. tire was $\frac{1}{3}$ as much as required by the sled. This data will be available in the Houghton test report when published. Additional tests on large diameter wheeled trailers will be accomplished this summer in Greenland.

A PROPOSED SYSTEM OF PHYSICAL AND GEOMETRICAL TERRAIN VALUES FOR
THE DETERMINATION OF VEHICLE PERFORMANCE AND SOIL TRAFFICABILITY

M. G. Bekker

Abstract

Vehicle performance and soil trafficability cannot be predicted by means of a single value. Since the problem closely resembles any other problem related to the evaluation of stress-strain relationship of structures, the engineering evaluation of performance and trafficability may be accomplished by adaptation of existing methods. To this end, a system of physico-geometrical soil values must first be established to conform with the general principles of applied mechanics. Such a system may be borrowed with certain modifications from Soil Mechanics as developed for civil engineering purposes, and supplemented with such generally recognized additional values as moduli of directional deformation, and exponents of empirically defined stress-strain curves of a soil under simulated vehicle loads.

This system of values, although based on unavoidable simplifications, appears to serve the purpose well from the engineering point of view, and is entirely compatible with systems developed in other areas of applied mechanics. It may thus aid the establishment of the mechanics of land locomotion which would describe in a comprehensive and systematic manner the physical terrain - vehicle relationship.

APPLICATION OF RECENT DEVELOPMENTS IN VISCO-ELASTICITY
AND PLASTICITY TO PROBLEMS IN SOIL MECHANICS

E. H. Lee

Abstract

In recent years the development of the theoretical analysis of stress and strain distributions in anelastic materials has progressed rapidly. This has been concerned in the main with plastic materials and with visco-elastic materials. Problems are now amenable to solution, or to the determination of certain properties of the solutions, by methods which were not available only a few years ago. The theory of both these types of materials has application in the field of soil mechanics.

The stress analysis of pavements and subgrades has commonly been based on the theory of linear elasticity, although it is known that many sub-grades are governed by much more complicated stress-strain relations which include permanent and delayed elastic response in addition to instantaneous elastic response. Application of the theory of visco-elastic materials permits the introduction of these properties, and methods of solution are now available for utilizing this theory. The solutions exhibit important qualitative differences from those based on elasticity; for example, under constant load the permanent flow and delayed elasticity lead to variation of the stress distribution with time.

Failure in soils has commonly been analyzed on the basis of the theory of plastic flow. Many new solutions to such problems have recently been developed, and the method of limit analysis now enables bounds on critical loads to be determined for problems for which the complete solution would be too complicated to solve by presently available methods. For example information on failure loads to three-dimensional problems can now be obtained. Problems of vehicle mobility come within the scope of this method.

In this paper these two fields are surveyed and some particular examples are discussed.

DISCUSSION

QUESTION (Spannhake): Most of these methods are very complex and, if you want to keep your analytical department busy, they can make for you all the necessary transformations which require lots of mathematical work. In these transformations the consideration of boundary conditions is particularly cumbersome, and I wonder whether you have not developed a simpler method which would do the job.

ANSWER (Lee): In recent years the use of the Laplace transform has become widespread in problems in Applied Mathematics, particularly in such fields as electric circuit analysis. Many tables of such transforms and their inverses are therefore available which can be used in the stress analysis problems of the type discussed in my paper. Since the visco-elastic analysis is linear, superposition can be used and any given problem can be broken down into simple components. Such a procedure can considerably simplify particular applications.

As detailed in the initial report on this method (Stress Analysis in Visco-Elastic Bodies by E. H. Lee, PA-TR/8, to be published in the Quarterly of Applied Mathematics) stress analysis problems in visco-elastic bodies can be transformed into elastic problems with the same boundary conditions, and in some cases this method of handling boundary conditions may be simpler than direct application of the Laplace transform.

DIMENSIONAL ANALYSIS AND SCALE-MODEL
TESTING IN MOBILITY RESEARCH

C. J. Nuttall, Jr. and J. P. Finelli

Abstract

The authors review the uses of scale-model tests and dimensional reasoning in off-road vehicle mobility work and outline the background of this development and the present state of the art. The earlier scale-model research upon which much of this paper is based appeared to have concluded a first phase satisfactorily on the basis of assuming explicitly a simple concept of the soil system in its relationship to vehicle imposed loads. More recent work on vehicle-soil relationships has apparently demonstrated a need for a more complex and extensive system of soil parameters. The theoretical and philosophical questions which this recent trend implies in relation to quantitative scale-model testing in soils are discussed. The authors recommend that research on the use of scale-models be resumed and suggest that one of its first tasks will be the re-examination of the state of the art in the context of recent developments of this sort. The authors conclude their paper by outlining the broad field in which they believe scale-models may presently be applied in immediate practical support of the designer in spite of the several theoretical questions which they raised earlier in the paper.

COMMENT BY M.G. BEKKER

1. I have always been impressed with the work of Mr. Nuttall in the field of dimensional analysis as applied to land locomotion problems.

His presentation gave an excellent review of the problem and methods available, and stressed that the first problem to be approached is definition of visco-plastic mechanical properties of soil and the means of measuring these properties. It was also mentioned that Dr. Reiner is working jointly with the Stevens Institute of Technology in this respect.

I hesitate to display my ignorance in this specialized field, but, if I may say anything on this subject, I would like to stress the satisfaction with which such a study should be welcomed. It appears to me that the main difficulties which Mr. Nuttall has emphasised stem from the lack of definitions and measuring methods of visco-plastic properties of soils.

This conclusion may also be deduced from the recent work of Professor E. McEwen and Mr. B.F. Willetts of the University of Durham (New Castle on Tyne) who investigated, by means of dimensional analysis, the sinkage of dynamically-loaded footings in connection with vehicle sinkage.

Both these investigators emphasize, for instance, that in a soil which is not a Newtonian liquid, the effective value of viscosity which has to be used in the Reynold's number is simply not obtainable. The late Mr. Markwick of Road Research Laboratories, who pioneered the application of dimensional analysis to vehicle problems, in England was of the same opinion.

I do not know if these properties are obtainable, and I would like to ask Mr. Nuttall for his comments.

2. Another remark which I would like to make refers more directly to the work performed by Mr. Nuttall. As I see it, his selection of dimensionless coefficients for scale model research has been rather limited and the whole field has not been thoroughly investigated.

Markwick, for instance, considered eleven variables: grain size, 2 linear dimensions of the footing, sinkage, density, cohesion, friction, kinematic viscosity, load, speed, and gravitational acceleration. These eleven variables gave eight non-dimensional numerics.

Mr. Nuttall mentions in his paper (if I recall correctly) 7 variables, and hence 4 types of dimensionless values. In his studies performed at Stevens, as I remember, only 3 dimensionless values were used in an experimental correlation of wheel systems.

Obviously, there is an almost complete freedom in trial selections of variables and numerics: McEwen, for instance, investigated sinkage similarities by using different dimensionless numbers from those by Nuttall. All this indicates that a more systematic program in this field is needed.

In such a study, of course, the question of the number of variables, and their meaning comes first. For instance the assumption of a certain density implies a homogeneity of soil, which does not exist. If we want to consider the change-in-depth of soil characteristics, we should, it seems to me, introduce such values as n and k which I discussed in my paper presented before this symposium.

The question is, how far shall we go? I would like to hear any comments which Professor Lee and Mr. Nuttall may make on this subject.

REPLY TO M. G. BEKKER'S COMMENTS

In discussing scale-model research, its specific objectives must be kept clearly in mind. On a theoretical plane, this research seeks to develop sufficient understanding of various types of problems, including importantly the relative consequence to their solution of each of the numerous possible system parameters, to properly design and conduct scale-model tests whose results may reliably be interpreted in terms of quantitative, full-size system behavior. It is not anticipated that a single procedure will be satisfactory for all types of problems and situations. The power of scale-model method lies in the fact that it can provide quantitative answers to complex problems in the absence of detailed, mathematically expressed theory, and without resort to lengthy analytical processes. The practical usefulness of the method depends in large degree upon the extent to which this potential is developed.

While, as Colonel Bekker points out, it is highly important to scale-model work to have an established system of valid, dimensionally meaningful soil parameters, and proper means for measuring them, it is not (surprising as it may seem) in all cases essential to the first steps of research on techniques and expansion methods. A sound, accurate concept of the factors influencing the shearing resistance of a soil, for example, is of paramount importance, but a detailed picture of the manner in which this is reflected in the final, measured results of an experiment usually is not indispensable. Thus, while we recognize that the first problem in extending our scale-model competence into the range of plastic soils is to understand thoroughly their mechanical properties, we believe that we may proceed quite a ways solely upon the basis of conceptual pictures of the type of behavior the soil will have under given circumstances; i.e., that we need not await the development of detailed techniques for measuring particular soil plastic properties before beginning exploratory scale-model research in plastic soil conditions.

With regard to the selection of variables for consideration, these are as always, both independent and dependent variables. The number of dependent variables included is merely a matter of what facet of system behavior is under study, and the detail in which it is to be examined. The number of independent variables is divisible into three classes: those characteristic of the object under test; those characteristic of the soil system in which it is to be tested; and, in systems where the phenomenon of gravity plays an unalterable role, the acceleration of gravity. In general, the size of the test object (describable by a single significant linear dimension where geometrically similar objects are involved - as they explicitly have been in all our past work), basic speeds, and basic loads, constitute the independent variables in the first group. In the second group fall the shearing resistance, tensile and compressive properties and mass density of the soil (and variation in these properties from point to point in the soil mass, and grain size, both implicitly covered by our statement of geometric similarity).

REPLY TO M. G. BEKKER'S COMMENTS (cont)

The independent variables connected solely with the mechanical scale-model are usually easily adjusted. The soil parameters and the acceleration of gravity are troublesome, however, and the object of the study in relation to each particular type of system (object and soil) is to find the smallest number of such parameters which will adequately describe the behavior to the desired accuracy; not to include everything. As already pointed out, the latter procedure can be used (erroneously) to prove that the whole proposition is theoretically impossible. The reduced number of soil parameters finally used in our early work as published, represents the findings of that particular research, and are not properly the subject of idle discussion without reference to the data, the type of soil, and the system used.

Differences in the form of the numerics utilized as between our work and that of others is of no particular consequence, all forms being derivable from any one complete set of numerics derived from the same list of variables. Choice of one form or another, however, does generally reflect the investigator's assessment of the relative importance of certain independent variables, where these are of sufficient number to permit of much choice, in relation to the several dependent variables, or his estimate of the most convenient form for use by designers, or for clarifying the picture for readers of his work. For example, dimensionless curves of lift and drag of an airfoil section are both frequently plotted in terms of the particular measured force divided by $\rho A V^2$, while in other instances drag is presented in terms of the familiar lift: drag ratio. Presentation in the latter form represents more of an interpretation of the results, but the information is identical, and the relationship between the two forms obvious.

DISCUSSION

Wiegel:

First of all, I would like to congratulate Mr. Nuttall for the nice work he has done. I have been myself concerned with similar problems, as I have done considerable research on hydrodynamics of ships and waves. However, any theoretical work we do has to be checked and tested on models, and I agree with Professor Lee that similar procedures are to be related to soil testing. Such tests should be continued at several places in order to cross check the results; for instance, in a wind tunnel you never get the same results in tests at two installations. The turbulence problem introduces many variables, and I imagine that a corresponding problem in soil testing might be moisture content.

Nuttall:

I don't want to appear gloomy about the present or future use of scale-models in soil-vehicle studies, but the facts are that for the last six years no one has done very much directly on the subject. When it comes to talking about the problem before a meeting like this, I am struck not with what was accomplished six years ago, but with such cracks as have appeared in the structure since. I am not saying that our earlier conclusions are wrong, but rather that they may be slightly off-course when we reexamine them with today's understanding. This viewpoint does not imply that I believe the theoretical situation is hopeless, or that we cannot use scale-models for many things right now.

Spannhake:

If you move in the horizontal plane, I think that everything is all right, but, if you have vertical motions of the soil or model, then you may get into trouble. I have a hunch that in such cases the gravitational forces may strongly affect your results. My question is whether you have considered this in your program.

Nuttall:

We did our work with simple rigid wheels of various sizes and shapes in a level, arbitrary soil. We assumed at the outset that gravitational forces might play a major role in such a system, although a wheel in level, soft soil hardly works against gravity in any obviously important way. True, it does some work both for and against gravity in displacing the soil particles to form a rut. However, we found it adequate in those circumstances to run scale-model and prototype wheel tests in the same soil, and to scale loads as the square of the linear scale ration, and speeds not at all. This result was equivalent to ignoring gravity effects. This may not have been a startling discovery.

DISCUSSION (Cont)

We have long recognized that if you change the type of soil, or type of test or test object, it would be necessary to reexamine this point, and that in many cases you will find that gravity must be considered as a system parameter. I believe this was discussed in some of our reports.

My present concern is that there appear to be still other parameters which must be dealt with in some situations; the deformation parameters of which Colonel Bekker spoke this morning and the visco-plastic parameters mentioned by Dr. Lee, for example. When these parameters cannot be ignored, they introduce both practical and theoretical complications. However, similar conditions exist in testing a ship model when, for example, neither gravity nor viscosity effects may be completely ignored. Neither quantity can be changed in any practical test procedure, and for this reason they dictate contradictory scaling procedures, particularly as regards model to prototype relationships. This dilemma is overcome by assuming one or the other to be of controlling importance, depending upon the type of test, scaling accordingly, and correcting the results for lack of proper scaling of the secondary factor by essentially empirical means. For example, in tests involving surface wave-making, gravity is more influential than viscosity, and speeds are scaled accordingly. Viscosity cannot be totally ignored where skin friction is involved however, and an empirical correction is used. Similar corrections can probably be made in cases where we have soil factors involved which can neither be handled entirely correctly nor totally ignored. I feel that problems about the most practical and satisfactory ways to do one thing or another in quantitative vehicle-soil scale-model testing, will in time be solved, if they are important enough, by experience, and perhaps some inspired, intuitive, but not necessarily rigorous factoring of the problem.

METHODS OF EVALUATING THE EFFECTS OF TERRAIN GEOMETRY ON VEHICLE MOBILITY

I. J. Sattinger

Abstract

The requirements for operating combat vehicles at the highest possible speed over rough ground makes it important to be able to determine the effects of terrain geometry on allowable speed. A research program is being carried out which should lead to methods of analyzing this relationship. Data on character, location, and frequency of occurrence of terrain geometry is to be collected and organized. Methods of predicting the dynamic response of a proposed vehicle operating at various speeds over rough ground without the necessity of a full scale test on a pilot model have already been developed. These methods make use of electronic computers to simulate the response of the vehicle. From the simulation, data can be obtained concerning rotational and translational displacements, velocities, and accelerations of the vehicle and forces and stresses at various points in its suspension system or structure. These dynamic response data can be compared to suitable performance criteria to enable the designer to judge the suitability of the design in terms of structural strength, effectiveness of the human occupants, and the performance of certain components, such as the gun stabilization system. The effect of speed on this performance can also be judged.

The available tractive effort and external resistance to motion are other important factors affecting the mobility of a vehicle. Methods of computing these quantities from known vehicle characteristics and physical characteristics of the soil are already in use. There are, a number of situations, for example, operation on a slope or over a vertical obstacle, where the terrain geometry produces non-uniform load distribution. To deal with these situations, an extension of the present analytical method is required. Mathematical techniques for accomplishing this analysis are discussed briefly both for steady-state conditions and for the dynamic case of continuous motion over soft, rough ground.

COMMENT BY L.C. BERNER

1. Mr. Sattinger has proposed an extension of the present analytical methods to study the motion of resistance and available tractive effort when the vehicle operates on a slope; or over vertical obstacles, where terrain geometry produces non-uniform load distribution.

It seems to me that such methods are already available. Actually, none of the existing vehicles display, in static condition, a uniformity of load distribution and this has always been considered by methods developed for that purpose. In the section entitled the "Determination of Available Tractive Effort", Mr. Sattinger actually uses those available methods.

Generally speaking, it is not clear to me why the problem of tractive effort has been brought up with reference to the evaluation of the effects of terrain geometry on vehicle mobility.

It is true that vehicle vibrations change the load distribution on driven and driving wheels or along the ground contact area of the track; this causes changes in motion resistance of the vehicle; which in turn changes the net tractive effort or drawbar-pull. However, the relationship between the change of load distribution due to a slope or bump action and the tractive effort, can be and has been established. What more is needed besides the refinements of presently available methods which apply static concepts?

If I understand properly, Mr. Sattinger proposes to extend these methods to allow the analysis of dynamic conditions, occurring when the vehicle travels over soft rough ground. It seems that this would lead to very complex "generating functions" and other costly arrangements in the analog computers plus extensive field tests of actual vehicles, in order to find out how they bounce, pitch and roll. Such work, although most interesting, appears to be of little practical value.

If the project is successfully completed, it will be found, for example, that in soft plastic terrain a vehicle traveling at a definite speed and hitting certain obstacles may nose down because of excessive pitching vibration. That, let us say, will increase motion resistance to such an extent that the vehicle will lack traction for a moment. But, if it is traveling fast, it will have, enough inertia to overcome the momentary spin of the track, or wheels, and keep on going. However, if traveling slow, it will not pitch, there will be no appreciable lack of traction and the vehicle will also keep on going.

What then would the study produce from a practical point of view?

In my opinion, the most critical terrain conditions, as far as traction is concerned, are caused by very soft, plastic soils, which extend deeper than the ground clearance of the vehicle and by virtue of their physical structure are flat and even. Thus the dynamic effect of ground geometry is negligible and not worth while for extensive testing. Moreover, in such soils a vehicle cannot travel fast. Experience does not show

practical speeds higher than 1-3 mph. At such speeds there are practically no vibrations and a consideration of static methods is quite sufficient to evaluate the tractive effort, or drawbar-pull.

Thus I would like to state again that an extension of these methods to analyze dynamic conditions, although theoretically interesting, would have little practical value.

2. Mr. Sattinger refers to the ride comfort index as developed by the Riding Comfort Research Committee. May I note that although this criterion would be of value in general considerations, it appears that the specification of the limit for maximum pitch amplitude may be accepted as a practical index of the riding qualities of a vehicle, or conversely, of the roughness of the terrain.

Such a criterion as shown in the studies by LEHR may easily be converted into allowable vehicle speed; it relates terrain geometry to mobility more directly than all the indices of "ride comfort".

It also seems that a study of seat comfort and the analysis of personnel behavior is a problem of human engineering rather than of research on vehicle mobility if we consider the latter in a purely physical sense.

REPLY TO M. G. BEKKER'S COMMENTS

1. In my paper, I brought out the fact that terrain geometry affects both the allowable speed of a vehicle and also in certain cases, such as operation on a slope or over a vertical obstacle, the available tractive effort. In presenting specific examples of calculation of available tractive effort for static conditions, use was made of already well-established formulas taken from Reference 1. These formulas certainly lend themselves to the calculation of available tractive effort for non-uniform load distributions. It seems, however, that additional experimental research is desirable for some of the more complex situations involving non-uniform load distribution, such as calculation of tractive effort and resistance to motion of tracklaying vehicles. Also, the process of determining load distribution on non-level ground may involve some complications under certain conditions, even for the static case, and the computer techniques referred to in Section 2.2 could be helpful in these cases. There is thus need for additional study of the effect of terrain geometry on available tractive effort.

The analysis of the dynamic case of continuous motion over soft, rough ground probably gives no useful information concerning available tractive effort as such. It might, however, be of interest to study this case to determine limitations on attainable speed and effects on tractive power input requirements and efficiency due to the combined effects of both the physical and geometrical characteristics of the ground.

2. As indicated in the paper, allowable speed of a vehicle over rough terrain will be limited by the effect on the safety and performance of personnel, structure, and equipment. The detailed investigation of these effects is, of course, more closely related to vehicle design than to analysis of vehicle mobility. They are, nevertheless, the basis for the establishment of criteria on allowable speed. If it is possible to demonstrate a clear relationship between maximum pitch amplitude and the abovementioned performance factors, as Colonel Bekker has suggested, it would certainly lead to a simplification of the problem of determining allowable speed.

DISCUSSION

QUESTION (Wiegel): What consideration has been given to including the physical characteristics of the ground in the determination of vehicle dynamic response?

ANSWER (Sattinger): We have been thinking about this problem, but our work to date has been based on the assumption that the ground is extremely hard. This would give the most pessimistic answers for shock loading. If the physical characteristics of the ground are to be allowed for, they could be represented by an equation of the form $p = k z^n$. I was particularly interested in Professor Lee's paper in which he uses equations for ground characteristics that might be transformed into electrical analogues. I don't see any reason why, by means of these equations, ground characteristics could not be taken into consideration.

(Spannhake): In the equations which you set up for analogue computations, you consider a tire to be a linear spring. Now, you probably take these values from static deflection tests, but we found out that in motion these values are changed by the torque applied to the tire and, if you consider this, you will never know from a static test what the actual behavior of the tire will be. We have made tests in that respect and there are other works which describe the behavior of tires in conditions which involve visco-elastic properties. We have not made any extensive tire testing, and this is one point which I would like to make, that if we are going to continue our evaluation, more tests will have to be made.

(Sattinger): In carrying out studies on the response of tanks, which use solid rubber in both tires and tracks, we have used a non-linear spring characteristic to represent the rubber, this characteristic being based partly on static tests and partly on estimates. I agree that we need more data in order to increase our accuracy.

(Lee): I am very interested in whether you have done anything with reference to the unsymmetrical loading?

(Sattinger): I am not sure I understand the question.

(Lee): For instance, if you have right-hand and left-hand track which do not bounce at the same time, your loads are not symmetrical.

(Sattinger): You mean that the right track might not go over the same obstacle as the left track?

(Lee): Yes.

DISCUSSION (cont)

(Sattinøer): Our work has been confined to the study of motion in the pitch plane, which assumes that both tracks are on the same obstacles. As far as the roll problem, of which you are talking, is concerned, I don't think there would be any great difficulty in setting it up for computer solution. However, since the problem would become a three-dimensional instead of a two-dimensional one, the amount of computer equipment required would be substantially increased.

DEVELOPMENT OF NEW TYPE TRACK BY THE ORDNANCE CORPS

Col. G. T. Petersen

Abstract

The history of military vehicle design for cross-country operation based on a "go or no go" basis was traced, and the many set-backs to progressive research encountered during war and peace time were amplified. The concept of grip failure advanced by Col. Bekker, including the latter's theory of a spaced-link track, was proven superior to conventional track design when so demonstrated by two experimental vehicles. The need for continued research on soil evaluation and mobility development by government laboratories and educational institutions was stressed.

DISCUSSION

QUESTION (Rucker): Why were so many three-inch grousers put on the experimental track, since this is exactly against the theory of Professor Bekker?

ANSWER (Col. Peterson): I must admit that I did not participate in that decision, but maybe Colonel Bekker will have the answer.

(Col. Bekker): I am afraid I cannot answer that question.

(Harshfield): That decision was made by the Studebaker Packard Corporation, not by Detroit Arsenal. Many experiments were needed to prove or disprove the theory.

QUESTION: Why were so many tests with different grousers made when you designed the Groundhog?

ANSWER (Col. Peterson): We didn't have much information at that time, only a bunch of drawings and the theory. We had to meet the deadline, and as Mr. Harshfield explained we had to experiment in order to show the advantages of the spaced-link track.

(Rucker): The main problem is whether tracks should be open or closed. The advantages in performance of an open spaced-link track are remarkable. However, we found out in recent tests performance in snow that an open track has a tendency to dig in in a deep snow. What then is actually the difference between spaced track and closed track? Should the track be necessarily open?

(Col. Peterson): We have observed the phenomena which you mentioned at Houghton, Michigan, and various solutions have been proposed. I don't see any conflict between our understanding of the spaced and closed tracks. Before you give any opinion, you must give first a good definition of the open track, then you may discuss its performance. Perhaps Colonel Bekker will have some comments.

(Col. Bekker): I hope I will not add confusion to this general picture, and I would like to say that there are two ways to cross a soft difficult terrain: you either go on the surface or beneath the surface on a firmer stratum. In the case of a light vehicle which is small enough to provide low ground pressures, it is possible to go on the surface of the ground. Then a large conventional track would be all right. In the case of a heavier vehicle, this may be impossible. However, even the lightest vehicles sooner or later must encounter soil conditions in which they will have to sink considerably. This appears to be inevitable. If it is inevitable, then the only solution is the spaced-link track which would let the vehicle sink as soon as possible and reach a hard stratum which may

DISCUSSION (cont)

help to develop the necessary traction and keep the vehicle going with the least of motion resistance. It thus becomes clear that for surface crossing the best would be a conventional track composed of a continuous chain of plates or rubber bands. For the sub-surface crossing, the spaced-link track, properly designed appears the only answer. Since the first case inevitably turns into the second case, the spaced-link track appears to be the only rational solution and the inevitable substitute for a conventional track. It is true that a spaced-link open track may sink a little bit deeper than a corresponding conventional track, but this does not mean that because of such an increased sinkage the motion resistance is increased. To the contrary, a deep sinking spaced-link track has less motion resistance in most cases than a low sinking conventional track. A comparison of sinkage between a spaced and conventional track cannot be considered as a measure of relevant performances. I would also like to paraphrase what Colonel Peterson said: The spaced-link track is an open track, but an open track may not necessarily be a spaced-link track.

DISCUSSION (S. J. Knight, A. A. Rula, D. R. Freitag, C. R. Foster)

Regarding spaced-link track

Colonel Bekker and Colonel Peterson have reported superior performance of the spaced-link type of track over conventional track in drawbar and slope-climbing ability in soft soils and snow. The spaced-link theory indicates the superior performance is due to the longer shear plane developed under the spaced-link track than under the conventional track. Mr. Doyle's discussion indicated the superior performance was due to the fact that the spaced-link track had an aggressive grouser, and could dig down deep and reach underlying hard layers. Also, the track produced low rolling resistance as it was forced into the soil and as it was extracted as the vehicle moved forward. High clearance and narrow belly also contributed to the superior performance. These statements, which were also supported by Colonel Bekker, lead to the conclusion that the superior performance is not due to the longer shear plane, as indicated by the spaced-link theory, but is due to the fact that the vehicles were actually not operating on the same medium. In addition, it is suggested that many of the vehicle design elements were not equal in the comparative tests.

It is therefore suggested that future tests be made with a full set of tracks whose individual shoes could be removed at will and replaced by other shoes with shorter or longer grousers. Also, it is suggested that the belly be raised or lowered by the removal or addition, respectively, of a false belly. Power should always be adequate to spin the tracks in a comparatively soft medium. In this manner truly comparative tests could be made.

During the testing, the necessity for complete information on the physical properties of the medium used to at least 1 ft below the maximum depth of rutting is emphasized. The testing should be accomplished in such a manner that it represents the conditions that develop under the track rather than the before-traffic condition.

M. G. BEKKER'S REPLY TO MR. FOSTER'S REMARKS

Mr. Foster has intimated, if I understand correctly, that the papers by Colonel Peterson, Mr. Doyle, and my own contribution to the discussion have not clarified the reason for the superior performance of the Spaced-Link Track; and that this performance may have its origin not in the high pull of the track as indicated by the theory, but in other elements of vehicle design like belly clearance, grousers, etc. Thus, Mr. Foster appears to have expressed doubts about the theoretical work so far done, and suggests special tests such as an investigation of vehicles equipped with false bellies which could be fixed at a desired level, tracks which would have shorter or larger grousers, etc., in order to find an acceptable answer to his question.

The answers to these questions, in my opinion, have been given on a theoretical and an experimental basis and have been described in the "Introduction to Research on Vehicle Mobility" published by Aberdeen Proving Ground and in numerous reports of tests and measurements listed in this "Introduction" and in CRO Report T-247. In addition, I believe, a satisfactory explanation of the problem is contained in two U. S. Patents: No. 2,708,608, Tractor track and No. 2,685,481 Spaced-link track, which define the nature of the performance of the Spaced-Link Track vehicle.

I do not know whether Mr. Foster made his suggestion because he is unfamiliar with the work done, or because he disagrees with it. If the first case is true, I have little doubt that the study of the available knowledge may satisfy the critic. If the second case is true, I should be very glad to discuss all the details and would appreciate more specific objections. As the matter stands now I would not see any justification to repeat the experiments and studies which were performed before 1948.

Before closing the present discussion may I again say that the invention of the Spaced-Link Track is not the essence of the problem. The most significant objective of our work, as I see it, is the establishment of principles and methods of evaluating soil-vehicle relationships; the Spaced-Link Track appears to be only one of the illustrations of the soundness of these methods.

This work has led not only to some new concepts of the track and wheel but may also lead perhaps to new concepts of a vehicle. The Groundhog is a good example: it incorporates not only a new track concept but it is based on a new approach to the design of the vehicle as a whole.

Mr. Doyle stressed that point very ably by calling the new types of vehicles under consideration the HT/LD type: High Traction/Low Drag vehicles.

I have been trying for some time to foster the idea that the form of cross-country vehicles is not quite rational as it has apparently been based on forms developed for highway operations. The necessity for a

M. G. BEKKER'S REPLY TO MR. FOSTER'S REMARKS (cont)

morphological change in vehicle design appears thus more pronounced today than the necessity for a technological change. The Spaced-Link Track is only one element of a morphological change which, in my opinion, has been thoroughly explored on the background of other changes in vehicle design.

DISCUSSION (S. J. Knight, A. A. Rula, D. R. Freitag, C. R. Foster)

Regarding soil constants

Colonel Bekker and others have stressed the need for constants of soil strength and deformation. The Corps of Engineers recognizes that a theoretical approach is desirable and that in such an approach basic constants are a necessity. However, we in the Corps also have an appreciation of the difficulties that are encountered in measuring these constants. This appreciation has been obtained in other studies that have been conducted on stress distribution in soils.

Experiments by the Corps and others in the field of soil-shear research have pointed out that the direct type of shear test has serious deficiencies. Nonuniformity of strain across the sheared surface and inability to control drainage of water from the soil during the shearing process are the major deficiencies. We consider the triaxial shear test as the best available at the present time for measuring values of angle of internal friction and cohesion. We did not measure these in our field correlation tests because they must be made on samples taken in a relatively undisturbed state. Sampling and testing in numbers adequate to yield useful information would have increased the cost of the program by a significant percentage. Our interest was primarily in soils at relatively high moisture contents where the angle of internal friction value is essentially zero. We have developed and published correlations between the cone index and cohesion. Since our activities have been broadened to include sands, which will have essentially zero cohesion, we are planning to make comparative triaxial shear and cone index tests.

M. G. BEKKER'S REPLY TO THE COMMENT BY MESSRS FOSTER, KNIGHT, AND FREITAG

Mr. Foster stressed the difficulties in measuring "soil constants" and referred to the studies by the Corps of Engineers.

It may be presumptuous on my part to discuss the matter as I am not a civil engineer, but for the sake of discussion I would like to present some views upon this subject.

I am in a full agreement with Mr. Foster and Knight that the measurement of friction and cohesion is extremely difficult and that the triaxial shear test is the best available. There is no doubt that, as Mr. Foster said, sampling and testing of soils by means of this test would extremely complicate soil exploration from trafficability point of view and increase the costs. However, one may ask the question whether such a test is really needed at this stage of our work and whether a simpler and cheaper one could not be substituted. In the opinion of a number of workers in this field and, in my own opinion, the answer is yes.

There seems to be a basic difference between the information needed for construction of buildings, dams and dikes and that necessary to predict vehicle performance, or soil trafficability. From a civil engineering view point, dangerous deformation of the ground may take place during a period of several years; in the case of a vehicle crossing a given area, the same occurs in the matter of seconds. That is why, as I see it, the proper techniques of boring, sampling and triaxial testing are so important in the civil engineers' work: it is necessary to know, not only the exact definition of what is meant by friction, cohesion, or other values which to my knowledge have not yet been fully defined, but also the history of the ground at a depth of several yards. The problem of soil consolidation due to the displacement of water must be treated in soil mechanics in a most complex way and with utmost care. Similar treatment must be given the load distribution at those great depths where one layer of soil rests upon another layer of different soil.

Such difficulties apparently do not exist in mobility research. First, if we assume that the largest track is three to four feet wide, the depth of the ground affected by loads does not exceed three or four feet, in most cases at such depth the homogeneity of soil may usually be assumed as falling within the accuracy of the measurements involved. This is not the case where a heavy building foundation is designed. The complex question of ground consolidation is simply non-existent because water has no time to flow through the soil pores in sizeable quantities during the short period of vehicle crossing.

Consequently, we establish that the so called "quick shear test" is entirely sufficient, at this stage of our ability to cope with vehicle performance, to measure friction and cohesion. Such a shear test performed by means of a shear vane, or even the "Soil Truss" developed by the Navy as Professor Converse has shown, produces quite reliable data.

DISCUSSION (cont)

True, these data do not express the friction and cohesion which Mr. Foster has in mind and which he apparently proposes to explore by means of the triaxial test. These values are merely coefficients of Coulomb's equation, but they suffice to predict vehicle performance in a given terrain with an accuracy of up to 10%. Reports which corroborate that conclusion are available.

It would appear logical then to continue along this line, as I have proposed in my paper, although this is not the ultimate solution; we must crawl, however, before we walk.

I would like to add that the strength of the ground, i.e. friction and cohesion alone, will not enable the automotive engineer to predict vehicle performance or soil trafficability by the same process in which a knowledge of the strength of a steel of which a bridge is made, cannot yield any indication of the load capacity which the bridge can bear. To this end, other values are needed which are related to the physico-geometrical characteristics of load supporting masses, and stress-strain relationships of soils. These values are numerous and were discussed in my paper. It appears now certain that trafficability and mobility of vehicles cannot be expressed in terms of a single value, and we should recognize that fact.

A RADICAL IMPROVEMENT IN THE DESIGN OF TRACKED VEHICLES

J. R. Doyle

Abstract

The Oliver Corporation has been actively following the development of a new class of vehicles which I would propose to call the HT/LD or High-Traction/Low-Drag class.

The integral part of these vehicles is the Spaced-Link Track and a properly designed chassis with the purpose of reducing drag and motion resistance. The general principles of this design have been established by M. G. Bekker and are being developed for military use.

The application of these principles to the design of commercial vehicles offers much promise; however, it would require the abandonment of a number of conventional concepts. Such a change in the present trends, which have been firmly established without a major deviation for the past 40 years, may be a healthy move in the right direction.

COMMENTS BY M. G. BEKKER

I believe that the proposal by Mr. Doyle not to refer to the spaced-link track as such, but to what Mr. Doyle called the HT/LD principle, that is, to High-Traction/Low Drag Vehicle, may help to clarify many questions.

I am not proficient in the coining of new words but if I may follow Mr. Doyle's line of thought I would propose a more general term for the new vehicles, which could express an idea of something like: Vehicles Morphologically Adopted to Any Duty Outside Roads, or an abbreviation, the METADOR-vehicles.

The presently used term of Spaced-Link Track, or in abbreviation, SLT-vehicles is definitely misleading. The term MATADOR may also be misleading because the vehicles in question have nothing to do with bullfighting, but experience shows that they have some of the agility of a matador and do not bog down and spin tracks as easily as the conventional vehicles.

THE EFFECTS OF POWER PLANTS
UPON VEHICLE MOBILITY

E. T. Vincent

Abstract

An analysis was made of a range of army vehicles, from which it was concluded that light-weight power plants alone are not a necessary requirement for mobility. An engine of zero weight and volume would not change the picture too drastically.

Other things being equal, the enclosing volume of the engine appeared to be the major consideration, particularly for engines of the type now employed.

The various types of power plants available today - Internal Combustion Engines, Gas Turbines, and Free Piston Engines - were considered for the purpose under discussion and when mobility, based on a power plant volume and fuel consumption basis, was considered, it resulted in the free piston design; perhaps offering the possibility of the major improvement in mobility providing its frequency of operation can be increased to the 2500 to 3000 cycles/min.

The possibility of burning gasoline in a compression ignition cycle was considered in order to keep a single fuel supply problem.

COMMENT BY M.G. BEKKER

1. Dr. Vincent has stressed an interesting relationship between the length of the engine compartment and the horsepower output of an engine: the length of the compartment equals $1/4$ of the engine output.

I would like to ask whether the author has considered that this may refer only to conventional engines. With radial or vertical arrangements of cylinders this relationship may not be true. Is this statement correct?

2. I was particularly interested in what Dr. Vincent said about the effect of weight and length of the engine upon mobility. Weight is not critical, however, length increase is. Dr. Vincent also stressed that the volume rather than the weight of the engine is important as far as the overall performance of the vehicle is concerned.

May I note again that this probably refers to conventional engines and to conventional locations of the engine. Non-conventional designs may completely change the picture if they prove to be of value in other respects.

In studies of motor vehicles forms we arrive at the conclusion that a radical change of performance and thus of mobility will probably not be accomplished through the invention of new power plants. It appears that an improvement in engines may change performance only slightly, irrespective of the degree to which engine design is revolutionized.

I believe that a similar conclusion may be drawn from Dr. Vincent's paper, and I would like to amplify this conclusion. In general, it appears at this time that future progress will result not so much from engineering changes of vehicle elements as from the basic change in vehicle forms. It seems to me that an encouraging, although perhaps inconclusive, proof of this fact is available.

According to the research work which I had the opportunity to perform at the Operations Research Office, Johns Hopkins University, a fundamental change in the form of a power package may increase vehicle mobility to a large extent. The philosophy of this idea is based on the observation that power plants, which were originally designed for road vehicles, have not changed their basic forms when applied to off-road locomotion, and may be visualized as bulky blocks of an unwieldy mass which has always presented difficulties to the designer who tried to mold them into the available space of engine and transmission compartments.

In addition, the presently available engine forms have a tendency toward what I would call an accessory form, whose shape is dictated by the accessories rather than by such basic engine elements as cylinder, piston rod and crankshaft arrangement.

Obviously, the accessory form may be molded in any conceivable shape while the envelope of a cylinder-piston-crankshaft-system cannot.

Now, if we agree to break one engine unit into a number of smaller engine units and if we reshape the accessory form of those units by producing, for instance, a thin, elongated, flat power plant unit, then it should be possible to distribute those units into the spaces within a vehicle body which are now partially wasted.

Thus the very large volume of the present engine compartment may be reduced, and a substantial increase in mobility may be achieved.

The philosophy of this solution is not based on a search for new engines, or thermodynamic cycles, but on the separation of the present bulky, rigid and unwieldy mass of the single engine into a number of smaller engine units. Such a power package may be molded and shaped by the designer in practically any desired manner. This idea was never investigated, although multi-engine drives have been used occasionally in the field of motor vehicle design; these applications were in many cases emergency solutions.

To further illustrate a potential advantage of such concept, I would like to mention the problem of fuel conservation, which Professor Vincent has stressed so ably in his paper.

With the multi-engine power plant it may be possible to devise automatic inclusion, or elimination of a number of engine units, in accordance with the changing resistance to motion encountered by the vehicle. Such a process would enable the working portion of the engines to operate at a minimum of throttled power, with up to 30 or more percent saving in fuel consumption even when using conventional, presently available engines.

I would appreciate Dr. Vincent's comment.

REPLY TO M. G. BEKKER'S COMMENTS

With regard to Colonel Bekker's question regarding cylinder arrangements and the effect on space, it is true that radial or vertical engines would change the picture, on the length effects. However the problem of the silhouette then arises if the engine is forward or aft of the turrett. In the past great stress has been given to the silhouette hence the low headroom vs engines. In the light of today's knowledge, perhaps a re-evaluation of the various engine shapes is desirable; though some non-conventional designs are being experimented with at the present time.

I am glad to hear that Colonel Bekker's investigations come to the same conclusions as mine, roughly. It is also noted that he stresses a complete re-arrangement of the power plant might be carried out with some advantage. In order to decide this, a rather extensive exploration period would be necessary, and it is believed, headed by an organization without existing engine commitments. Possibly it is the type of contract a University would undertake particularly where engine experience is available and some good young men who have yet to be molded into a definite pattern are also available. The results of such a study could then be submitted to experts in both the vehicle and engine fields for final analysis.

If some specification of R.P.M., B.H.P., desired S.F.C., etc., could be laid down plus the ideal shape of the vehicle, then much might be done in the desired direction of fitting the power plant to the vehicle.

DISCUSSION

QUESTION: Do you have any chance of burning low octane gasoline in the high compression engines?

ANSWER (Vincent): The problem of burning gasoline in compression ignition engines is that of temperature: the two-cycle engine with its increased temperature has a definite advantage. I think if an opposed piston uniflow engine could be devised for the purpose, the problem could be solved satisfactorily.

ANALYSIS OF A HIGHLY VARIABLE TORQUE POWERPLANT
FOR CROSS-COUNTRY VEHICLES

W. I. E. Kamm
Presented by T. R. Gondert

Abstract

Operation of a vehicle requires highly variable torque to overcome the various driving resistances. This is presently accomplished by the use of a transmission which results in considerable speed loss.

An engine capable of a 4 to 1 increase in torque over a normal engine of comparable size, is presented here. This torque increase would result from a BMEP of 450 psi made possible by the high, 65 psia, inlet air pressure. To withstand the high heat release present with this BMEP the engine has been designed with two parameters in mind: first, the reduction of peak pressures by the combustion chamber design; second, the insulation from heat, of those parts that are highly stressed. Conversely, load is minimized on those parts that are hot.

In addition to higher speed under normal conditions of hill climbing, soft soil, etc., another consideration is possible with the principle of high torque, high speed operation. The tracks of a vehicle could be designed to provide dynamic lift in fluid and semi fluid soils. With lift as well as traction available, it becomes possible to operate vehicles in areas that previously had offered too great a resistance to make movement possible.

COMMENT BY M.G. BEKKER

1. The challenging paper by Professor Kamm presents a new concept, not only in the unusual design of a compound Diesel-Turbine engine but also in the decentralization of the power plant. I do not feel competent to comment upon novel ideas regarding the design of the engine, but I would like to note again that the concept of the "decentralization" of one power package appears to have a deeper significance than is generally realized.

During the discussion of Professor Vincent's paper, I tried to present the philosophy of multi-engine power plants, when located in accordance with the requirements of space economy. May I now add that the idea of a decentralized power plant as conceived by Dr. Kamm on the basis of engine design considerations rather than morphological considerations of vehicle design, appears to be within the realm of this more general concept.

Referring to the lift action of rapidly slipping grouser plates of a track, it seems that we may encounter insurmountable difficulties.

The speed of slippage, which the author of this interesting idea considers, is of the magnitude of 60f/sec. or approximately 41 mph. At such speeds the impact forces may have a smashing effect upon the strongest steel alloys and it may be difficult to design even a short-lived track structure. We also have trouble in this respect with conventional tracks, which slip at but a small fraction of a mile per hour.

The reduction of slippage speeds of the proposed track may lead to unacceptable track dimensions, as they increase with the minus square power of the speed.

Has this problem been considered in more detail?

REPLY TO M. G. BEKKER'S COMMENTS

The slip speed of 60 FPS would be used only in conditions approaching water as to fluidity. Impact under these conditions should not present too great a problem.

Colonel Bekker's statement as to the destructive effect of a small fraction of a mile per hour slip is not clearly understood, however, it is assumed to mean relatively high vehicle speed, with very slightly higher track speed. Under this condition of high vehicle speed, the slip of the proposed track would be the same as for a normal track. The proposed track, however, would run on a continuous rubber strip for hard ground and highway travel, with the grousers retracted. The impact forces would, therefore, be less than for a track with steel grousers on the ground, or even for a track employing intermittent rubber blocks.

The high slip speed track is presented as a design concept and a serious research and development program will be required for realization of its principles.

DISCUSSION

QUESTION (Spannhake): I am very interested in the constant power machine as opposed to constant torque machine, because the advantages of the first are obvious in locomotion. However, I have a few questions. One is how would you control part load and, second question, when you run at high speed and low torque, how would you control the high pressure in the cylinders, because you do not need it at high rpm? If you consider merely purely adiabatic compression, then when starting with 65 pounds psi, you will find that the efficiency of the engine will be very low. You don't need that pressure at high speeds and low torque and you have to dissipate the heat which will generate due to supercharging. Have these problems been considered?

ANSWER (Gondert): In the engine under discussion, the supercharger-turbine section is mechanically independent of the engine. A low pressure combustion chamber is provided between the supercharger and the turbine. When the required torque exceeds that available from normal exhaust driven supercharging, the low pressure combustion chamber is used to further increase the inlet air pressure at the engine. The control of this supplementary combustion chamber could be either manual or automatic.

The supercharger-turbine will tend to be self-controlling up to the point where the auxiliary combustion is needed, as an increase in required torque will be met by increased fuel injection which will in turn increase the energy level of the exhaust gases. This then boosts the turbine RPM and thereby the supercharge pressure.

The supercharge pressure will therefore be dependent on required output and there is no particular excess of air.

The auxiliary combustion chamber would be useful as a starting aid during low temperature operation or when the battery is low.

MOBILITY EVALUATION
BY MEANS OF FIELD TESTS IN SOFT TERRAINS

C. W. Wilson

Abstract

The author defines vehicle mobility in a given terrain as the "ease" with which the vehicle moves about in that terrain and proceeds to review and discuss the various tests used in the field for evaluating off-road mobility. He concludes that simple, objective, readily interpreted tests which factor the mobility problem into consistent, manageable sub-problems before collecting the data, and which can be run in a wide range of terrains, best serve present needs. He stresses the necessity for as complete terrain information as possible to supplement vehicle performance measurements and points out the desirability of tests in deliberately simplified terrains from the point of view of reproducibility of conditions and results, description of the terrain, and analysis of the results. Soil measurements should include as a minimum, moisture content, specific weight, and measured in situ shear strength as a function of normal loading and shear travel. He concludes that at the present the most useful type of test is a drawbar pull-sinkage-trim test and outlines from his experience the specifications for proper tests of this sort. He stresses the primary need for standardizing a rational testing procedure in order to facilitate the interchange of vehicle test data among the many agencies which develop and/or utilize such information.

COMMENT BY M.G. BEKKER

1. In the chapter on a definition and testing of mobility Mr. Wilson has referred specifically to my proposed definition of mobility.

In connection with these references he quoted one of my earliest works on this subject but did not quote the latest one which was published by the Operations Research Office, Johns Hopkins University. (ORO T-247, 1953).

It seems that this omission has lead to a certain misunderstanding of ideas discussed. It would appear that Mr. Wilson tends to oversimplify the problem of mobility and the whole philosophy of this idea. Mobility, in the physical sense, cannot be defined and investigated as a quality of a single vehicle on a single course, because of the variety of factors governing vehicle performance in cross-country operation; it appears inevitable that mobility can only be recognized as a statistical value related to a number of vehicles operating in sample terrain. Thus mobility cannot be "tested" by means of drawbar-pull, or other performance indices but must be evaluated by operational analysis and by means of other concepts than those accepted at the proving grounds. Such a test as that of a draw-bar pull can never be, in my opinion, the measure of mobility; it is only the measure of a single type of performance.

I fully agree with Mr. Wilson that there is a great need for a better scientific approach to vehicle testing, but contrary to his opinion I would say that such testing will only provide material for the organization of operational tests which would eventually lead to the statistical determination of mobility. Moreover new methods and tools are needed in order to improve the present proving-ground techniques.

To conclude these remarks I wish to stress that mobility does not appear today to be an "ease" with which a vehicle is moving. It is a statistical value whose practical definition may be satisfactorily established, by appropriate operational research if we as automotive engineers, provide that research with necessary physical data.

2. On page 6, Mr. Wilson states the importance of making sure that proper terrain parameters be considered, so that controlling ones are not overlooked and those which are negligible are not included. In conjunction with this statement, the work by Dr. Nichols on dynamic properties of soil is quoted. What did Mr. Wilson have in mind when making that quotation?

3. I believe that the first proposal regarding the application of Coulomb's equation to the evaluation of the tractive effort was made earlier than Mr. Wilson quoted. The credit should go to Mr. E.W.E. Micklethwait who published his classical paper on 1 March 1944 under the title "Soil Mechanics in Relation to Fighting Vehicles".

4. May I also make a statement which should dispel some misunderstanding in regard to vehicle tests made in Canada. Mr. Wilson stated that recent tests in snow at Kapuskasing by the Canadian Defense Research Board included for the first time measurements of the effect of a towing hook, height and weight distribution on vehicle performance. To my knowledge such measurements and pertinent analysis have always been included whenever required.

REPLY TO M. G. BEKKER'S COMMENTS

1. Agree in principle, but have yet to see any practical field work along the lines suggested. Present drawbar pull-slip approach should not be dropped, but rather supplemented. Quantification of total mobility concept by means of operational analysis does not seem to change basic concept of "mobility" as "ease of movement."

2. Suggest reader consult references, which give excellent example of some of the properties which become significant, as the type of problem changes.

3. Colonel Bekker is apparently correct; earliest publication of the Auburn work which suggests the relationship of the Coulomb line and vehicle work was in May 1945. Micklethwait's prior work was not available to us until several years after that, and the relative dates have not hitherto seemed of major importance.

4. Believe paper was misread. Problem has been widely theorized upon, but there has been little data to indicate the practical influence of these factors upon drawbar test results. Recent Kapuskasing snow test results were merely cited to indicate the order of the effects, so that future discussions might be less heated and more enlightening.

THE PERFORMANCE OF TRACKED AND WHEELED VEHICLES IN SNOW

J. G. Thomson

Abstract

It has been shown as a result of many surveys in Canada and other parts of the world that snow depths seldom exceed 30 to 36 inches on the plains. Specifically those limits apply to the Canadian Sub-Arctic and very probably also to eastern Siberia and mid-continental Russia. Early season snow in these areas is very light, fine grained and weak structured. From approximately mid-season onward these snows can be expected to undergo progressive metamorphism until the pack is almost entirely depth hoar. At this latter stage the snow has sufficient mechanical structure to impoverish vehicle mobility performance but insufficient structural strength to support the vehicle or provide good traction. Thus, in effect, frontal motion resistance is provided by a structured snow while traction and flotation are provided by a disaggregated snow.

It is suggested therefore that design of wheeled or tracked vehicles might allow for mobility by means of:

- (a) maintaining low sinkage for light weight high speed vehicles
- (b) providing narrow wheels or tracks and high belly clearances to allow operation on the relatively hard underlying surface at deep sinkage
- (c) providing sufficient wheel or sprocket torque to allow for a device to modify the snow structure or remove it sufficiently to make a significant reduction in motion resistance.

Sufficient information is currently available to vehicle designers to allow them to design much more mobile vehicles than are currently in the hands of the users.

COMMENT BY M.G. BEYMER

1. Mr. Thomson has stated that there is "no snow mobility problem within the limits of the snow areas covered by (this) paper which cannot be solved on the basis of information currently available to vehicle designers". It would appear that such a statement is over-optimistic. If the situation were as Mr. Thomson states, why then would the National Inventors Council of the Department of Commerce place an efficient over-snow vehicle on the list of urgently required inventions?

I did not have the opportunity of reading Mr. Thomson's paper in full, but from the available abstract, I would be inclined to deduce that his optimism stems from the same concept of mobility which Mr. Wilson has propounded in his paper.

In my opinion there is very little information available as to how to design an efficient and economic snow vehicle which would satisfy modern requirements, and the statements made at this symposium by other speakers appear to confirm that conclusion.

If I may voice further comments in regard to Mr. Thomson's presentation, I would say that in the future we may not need specially conceived and designed instruments and apparatus as much as we may need a more fundamental knowledge of snow mechanics, and locomotion mechanics in order to make the existing concepts of test equipment a success.

REPLY TO M. G. BEKKER'S COMMENTS

I wish to stick to my opinion that achieving effective vehicle motion in the Arctic in winter time is not extremely difficult, but wish also to qualify that statement by saying that you must be willing to accept certain types of performance. From the point of view of a civilian operator this is quite acceptable. If you want, however, to state the method by which a given transport problem must be done rather than to state to where and by what time the supplies are to be delivered, then the problem is different but the possibility of solution from presently available information still exists. The restrictions which presently make it almost impossible for the military to achieve effective vehicle motion in the winter time Arctic are those which state vehicle characteristics in detail without giving proper consideration to the capabilities of the media in which the vehicle is to operate.

It is my opinion that the priority accorded the requirement for an efficient oversnow vehicle by the Inventors Council of the Department of Commerce is quite justified. Such a vehicle does not exist. However, such a vehicle could exist today if a well engineered application of presently available information were applied without the compromises occasioned by statements of military characteristics.

The closing comment, "--- we may not need specially conceived and designed instruments and apparatus as much as we may need a more fundamental knowledge of snow mechanics and locomotion mechanics---", is not in itself consistent. We can know nothing of snow mechanics until we can measure the mechanical characteristics of snow. It is still necessary to conceive and design the instruments for this task.

MOBILITY PROBLEMS OF THE NAVY IN THE ARCTIC

John T. Tucker

Abstract

Basic military requirements are made more difficult during Arctic operations owing to the added rigor of the climate. The chief problems then become the maintenance of bodily comfort, mobility of the transport systems and the maintenance of equipment. Continual research and development are required to insure the capability of successful year-round operation. The present status of such effort is amply noted by the fact that the most practical method of transporting heavy freight and bulk cargo is still by use of the tractor drawn sled trains at a speed that seldom exceeds 2 miles per hour for any 24 hour period, and this is only feasible during four months of the year.

If strategic requirements indicated the necessity of overland Arctic freighting operations during the "break-up" or "freeze-up" period, there is yet no vehicle available to undertake the operation with any assurance of success. There has been some recognition of the problem, as indicated by specific equipment modifications, individual project efforts and the delineating of broad overall requirements. These requirements are so encompassing, however, that meeting the year round Arctic transport specifications would at the same time solve all the mobility requirements of the Armed Forces for any area on the world's surface.

DISCUSSION

QUESTION: How fast do you estimate your tundra truck will go?

ANSWER (Tucker): Well, we certainly hope that the vehicle will go faster than we walk. The estimated speed is about 17 mph.

A REVIEW OF CORPS OF ENGINEERS -
AIR FORCE STUDIES ON FLOTATION LANDING GEAR

F. M. Mellinger and J. P. Sale

Abstract

In an effort to alleviate the time requirements for constructing forward Area Airfields in time of war, the U. S. Air Force initiated a program for the testing of specially designed large contact area landing gear configurations, called flotation landing gear.

The Corps of Engineers conducted a series of field taxi tests on unsurfaced subgrade soils at some 26 airfields throughout the United States, employing prototype aircraft (C-82, B-50 and B-36) equipped with various type flotation landing gear. A second series of controlled accelerated traffic tests with the flotation gear in a load rig were conducted on specifically constructed subgrade test sections.

The field taxi test with the prototype aircraft were analyzed on the basis of measured subgrade deflections in the individual test areas and the theoretical pressure distribution of the particular landing gear in question. Those tests also served to rule out current concepts of track type landing gear using a bogie and belt system as a means of attaining flotation and placed emphasis on low pressure, large contact area pneumatic tires. The accelerated traffic tests were analyzed along the lines used in establishing flexible pavement requirements for aircraft. The results of the two test programs have been correlated and methods developed for the design and evaluation of flotation type landing gear, operating on non-surfaced, or minimum surfaced landing strips.

COMMENTS BY M.G. BEKKER

1. Mr. Mellinger has described an interesting attempt at the application of a tracked landing gear and high flotation tires to an airplane.

The results of the test were stressed in the following conclusions:

- 1) The track belt does not carry much load between bogie wheels.
- 2) Conventional tracked landing gear requires exceptional maintenance care.
- 3) Under wet surface conditions, neither a low pressure tire nor a track can operate.
- 4) Also, in loose soils, normal operations are impossible.

As I had the privilege, to be consulted in 1950, by the Air Force and the Corps of Engineers on some subjects related to this development, I would like to take this opportunity to give my views as presented at that time:

- 1) There are certain theoretical methods which enable one to compute and estimate with relative accuracy the stress distribution and corresponding strains under a belt of the track and under a low pressure tire. The findings by means of this method are in full agreement with the findings reported by Mr. Mellinger, and show high local concentration of stresses.
- 2) Computation of soil deformations for a tracked landing gear and low pressure pneumatic tire indicates that the presently available "high flotation" landing gear can only operate on very hard compacted soils having the subgrade modulus, or as we call it modulus of deformation "k", equal to or larger than 200. This has also been confirmed by the Corps of Engineers test.
- 3) Thus, Soils below this value cannot be used as landing strips, although there are large areas of cultivated soils, steppes, and meadows, for instance, which offer large flat surfaces suitable for landings and take-off's of airplanes. This seriously limits the use of tactical aircraft.
- 4) To meet such requirements I conceived a landing gear for an aircraft which:
 - a) Carries the load evenly distributed along the whole track belt, without the local concentration.
 - b) Should require minimum maintenance as it has no wheels, rollers or springs.

- c) Should provide ground pressures of the order of a few pounds per square inch instead of approximately 70 psi's as produced by the existing "high flotation gear".
- d) Such a gear can even be adapted to a larger craft and enable it to land on loose soils.

This idea has been widely discussed and generally conceded to be possible. It has also been recognized that it may find an application in land-operation motor vehicles. In line with this assumption, arrangements are being made for the production of a pilot model of the proposed gear.

This gear is based on the principle of a skid-type suspension. As indicated on the following picture, it is composed of a stationary pneumatic cushion which supports a rubber belt track.

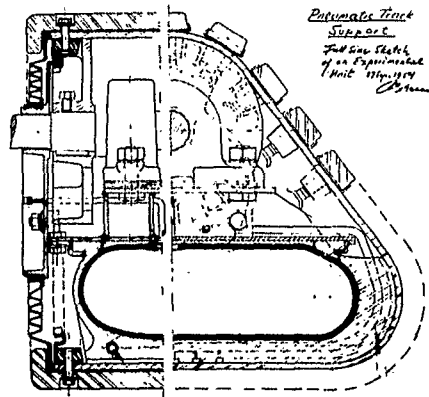
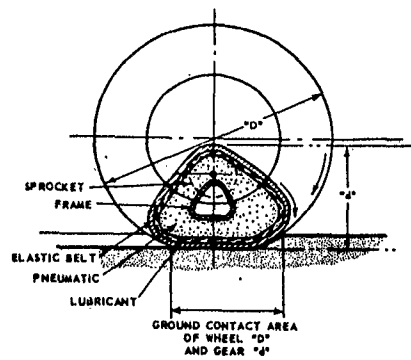


FIGURE 1

The track slides on the cushion, and the sliding surfaces are lubricated. Laboratory experiments indicate that in such a case there exists a large variety of lubricants ranging from water, containing soap, to dry talcum, which produce extremely low friction. The rubbing surfaces are sealed.

The next picture shows a sketch of an experimental model presently considered for production.



Comparison between the Height of a Regular Tire and
a Corresponding "Triangular Wheel"

FIGURE 2

REPLY TO M. G. BEKKER'S COMMENTS

(1) With regard to the statement that current tracked landing gear and low pressure pneumatic tires are only capable of operation on a subgrade modulus "k" in excess of 200, it must be realized that the required strength of the subgrade is greatly influenced by the weight of the aircraft in question. It is known for example that a C-82 aircraft equipped with its conventional tire gear can operate satisfactorily on a "k" value of 75 for a short period of time. This aircraft weighs approximately 45,000 pounds. The statement is correct, however, when speaking of such aircraft as a C-124, weighing 200,000 pounds. Neither of these aircraft, however, have been equipped with recently developed low pressure flotation tires.

(2) Several factors must be considered in the design of any type flotation gear. The aircraft designer is extremely reluctant to penalize the performance of his aircraft from the standpoint of payload, speed, or range, by installing landing gear that is either heavy or space consuming. Admittedly, almost any desired degree of flotation could be provided at the expense of one or more of these factors.

(3) In view of the fact that the thrust to weight ratio of some of our more recent aircraft is approaching 1.0, it is likely that special purpose aircraft with skid type gear similar to that described by Colonel Bekker will be feasible. The high thrust to weight ratio will minimize the effect of drag for such gear when the aircraft is taking off.

MOBILITY IMPROVEMENT FOR USAF AIRCRAFT
AND MISSILE GROUND SUPPORT EQUIPMENT

Lt. J. H. Frye

Abstract

As a result of numerous difficulties encountered by the Air Force in tactical operation due to inadequately mobile equipment, the Equipment Laboratory, Wright Air Development Center, established a committee to study the problem of vehicle mobility and formulate a set of mobility standards for Air Force ground support equipment. The report of this committee indicated that improvement was necessary in three general areas.-

(1) Wheels used on ground equipment, (2) Casters used on this equipment, and (3) General Mobility.

During the past three years, considerable improvement has resulted from following the recommendations made at the completion of this study. First, a specification covering standard wheels and hubs for industrial pneumatic tires has been prepared and put into effect. Second, four specifications have been written covering the various types of casters used by the Air Force. WADC is now testing casters built to these specifications to establish qualified products lists. Third, a contract was recently finalized under which a series of utility trailers are to be designed and standardized for Air Force use. Finally, in an effort to assure adequate mobility by furnishing proper guidance to equipment manufacturers, a specification covering general mobility requirements of ground support equipment has been prepared and released.

Considerable work remains to be done in an effort to obtain optimum vehicle mobility, but the ground work represented by the above specifications and standards provide a good foundation for maintaining a sound mobility program for Air Force ground support equipment.

MOBILITY - TIRE

Willard D. England

Abstract

The pneumatic tire is the foundation of vehicle mobility. Evolution of the tire has been through the development of materials and design and production techniques.

Due to lack of materials and molds and to Logistics of Supply during an emergency, Ordnance development has centered on a compromise tire to provide an adequate product through one construction. Mobility is effected through deflection controlled by inflation. By constant testing, obtained to a large degree through cut and try methods, we now know the deflections of certain tires for optimum performance under certain conditions. Coupling Engineer Corps Mobility Index with empirical test data has already removed some of the costly cut and try methods.

Mobility efficiency has been confined to the size of hole provided for tire application. Vehicle design engineers must recognize the fact that the tire is the primary means of providing vehicle mobility.

It is believed many of the problems of mobility can be worked out by a more scientific approach in engineering and design procedures as the technology of new materials increases and new means of tire stressing are evolved.

DISCUSSION

QUESTION: What is the possibility from the maintenance point of view to use tubeless tires for a tactical vehicle?

ANSWER (England): We hope that the tubeless tires may be introduced whenever required although one must realize the difficulties involved. If we get enough deflection and enough flotation with a tubeless tire, then the problem would be solved. However, from the taxpayer's point of view, I must mention that the cost of changeover at the moment would be very high.

QUESTION: I don't know whether Mr. England's suggestion to his cohorts of the tire industry was the invitation to speak, but I would like to ask what is being done in order to operate tires at low pressures, below 25 pounds psi?

ANSWER (England): I am not the tire carcass engineer, and there are many here, but I believe that this is a very important question. We have been working on this problem and the industry was good enough to design for us tires which operate at fairly low pressure without generating much heat and losing strength.

SPEAKER: I agree that tire design for high deflection and low speeds is quite satisfactory and that we must work on a similar tire which could economically operate at higher speeds. I think that on this problem Dick Kerr of American Arabian Oil Company, who has been working on tire inflation tables and mobility, can give us some answer.

(Kerr): In our operations we have found how the lower the pressure, the better the performance. If you want to really go, you have to bulge your tire, but the life and economy will not be satisfactory. The testing of factors of mobility and tire life are extremely complex, and it takes from six to nine months to find out just a small detail. I don't think we know very much about the problem and certainly there remains much to be done.

VEHICLE DESIGN CONCEPTS MOST ADAPTABLE TO HIGHWAY BRIDGES

E. L. Erickson

Abstract

Highway bridges are designed, under the AASHO Specifications, for standard live loads of various intensities, occupying traffic lanes of 10-foot width. These live loads provide for the passage of vehicles of legal size and weight. An allowance for impact is included to cover the effects produced by the motion of the loads.

The hypothetical heavy military vehicles whose effects on bridges were analyzed, exceeded the 96-inch legal width by considerable amounts. Because of these greater widths and also because of the fact that they are to travel only along the centerlines of the bridge roadways, it was assumed that their weight would be distributed over 1.50 traffic lanes. Limited test data verify the validity of this assumption.

The analyses of the effects of these vehicles were made on structures of the lightest type consistent with first-class construction in order that the computed overstresses would be the greatest. The results may safely be applied to structures of heavier types also.

Certain overstresses are permissible in structures in good condition for vehicles which are to make only occasional trips or only emergency trips. An overstress of $33\frac{1}{3}$ percent is considered safe for occasional use and $66\frac{2}{3}$ percent for emergency use. These limits were determined with considerable care.

At speeds of 5 mph. the effects of impact are practically eliminated and the stresses are nearly those from static loads. In some cases, it was necessary to restrict the speed of certain vehicles to 5 mph. in order to remain within the allowable limits of overstress.

The results of the study indicate that 8-axle vehicles of the tractor-semitrailer type appear to be the most adaptable to existing structures. The load on any single axle should preferably not exceed 24,000 lb.

VEHICLE DESIGN CONCEPTS MOST ADAPTABLE TO HIGHWAY PAVEMENTS

Fred Burggraf

Abstract

This paper describes the development of instrumentation and the results of field measurements of stresses and deflections caused by controlled traffic tests of heavy loaded vehicles as revealed by full scale road tests.

Load-stress and load-deflection relations for vehicles operating in different transverse position on pavements of different strength are discussed as are also the influence of wheel arrangement on stresses and deflections and the effect of single and tandem action.

A brief outline of a comprehensive road test project which will furnish, due to advances in instrumentation, additional basic data on both the performance of the vehicle and the reaction of different pavements is also included.

SHORE TRAFFICABILITY AS RELATED TO ENVIRONMENT

R. L. Wiegel and Parker D. TruMask

Abstract

Trafficability basically depends upon the physical characteristics of the soil and upon the geologic history, or things that have happened to the soil. It is convenient to measure these physical characteristics of the soils in terms of shear strength, angle of internal friction, cohesion rolling resistance, water content, or some other direct index of the behavior of the soil when a vehicle passes over it. But these strength characteristics depend upon the extent to which individual grains are locked or pressed together, the water content, physical and chemical forces, electrical charges, length of time the sediments have been loaded, and other characteristics. These physical and chemical aspects of soils are functions of environment, that is, the climate, source materials, biological activity, topography, or state of roughness or smoothness of terrain, length of time the processes of soil or sediment formation have been going on, amount of loading, and other geologic factors.

Similar environments produce similar types of trafficability. If the relationship of given environments to trafficability is known, then the trafficability of beaches and terrain in areas of future military operations can be predicted or inferred by recognition of the particular type of environment that prevails in such areas. Air plane photos, and soil or geologic maps are means by which particularly environmental types can be recognized in military areas where access is limited. Thus, geologic and other studies of the characteristic features of different kinds of environment with respect to trafficability offer means of aiding military intelligence with respect to trafficability problems in strategic planning. Investigations of this type are complicated and difficult, but they offer tangible means of assisting with a difficult military problem. Some of the general principles of this method have been used by the U. S. Navy Photographic Interpretation Center and the U. S. Geological Survey in preparing intelligence reports for military operations, but no definite study of the physical cause of trafficability has yet been undertaken with the specific object of determining how trafficability varies in individual environments so that such information can be used in predicting trafficability in areas of military interest.

As a result of a survey by the University of California, a considerable amount of data became available regarding the trafficability and environment of various types of shores. The summary of trafficability and environmental studies to be presented is an extension of this survey. It will be presented in three sections. The first section will contain information relating trafficability of vehicles to certain environmental features, the second section will present several shore classification systems, and the third section will contain information relating shore materials with environment. The study of trafficability of shore soils is of great interest, as it points up a problem which is exaggerated as compared with inland soils - that of change. Beaches are more or less in a dynamic equilibrium condition, while inland areas are in an essentially static equilibrium condition.

DISCUSSION

SPEAKER: We have been making many tests on beach trafficability using penetrometers, and the results were in agreement with those which Mr. Wiegel has reported.

WIEGEL: I am very glad to hear this. When I was writing my paper, I knew that the Corps of Engineers was going to report on cone penetrometers, and so I did not refer to this problem in detail.

QUESTION (Simon): Did you study the relationship between slopes and the type of soil of which they are made?

ANSWER (Wiegel): Yes, we made many observations, and in general were able to relate the slope with the median diameter of the sand. By slope I mean the slope of the beach face - that section of the beach which is exposed to wave and tidal action. In general it was found that the coarser the material, the more steep the slope. It was also found that the moisture content of the beach face (also called the foreshore) was generally higher than the moisture content of the berm.

(Kerr): We have found out that the slope-climbing ability of a vehicle is related to the angle of repose of material of which the slope is made. At higher slopes, for instance slopes reaching the value of 60 per cent, the effect of the angle of repose tends to reduce considerably the climbing ability of the vehicle. These properties should be taken into consideration when evaluating slope performance on the beaches. The angle of repose of sand is approximately 30°. Have the angles of other beach soils been investigated, and how do they affect performance?

(Wiegel): No, we have not considered this aspect of the problem. We found out that the failure of a DUKW on the slope of a cobble beach was caused mainly by the slippage of the wheels on the cobble surface when it is wet. Tracked vehicles would fail on steep slopes when going up them at an angle due to the slippage of the tracks off the boggies.

QUESTION (Glockler): I have one question. Have you investigated any chemical ways of consolidation of beach soils?

ANSWER (Wiegel): No, we have not investigated this subject. The U. S. Naval Civil Engineering Research and Evaluation Laboratories at Port Huenene had some contracts on this type of work (with Dr. Hans Winterkorn) in which certain chemicals were used for soil stabilization. The results of full scale tests showed the method to be satisfactory.

QUESTION (Col. Bekker): How soon do you expect to have some kind of geological indices which would help to evaluate soil strength from trafficability point of view?

DISCUSSION (cont)

ANSWER (Trask): This problem has turned out to be more complicated than I hoped it would be. We had quite a bit of difficulty getting the sedimentation machine to operate. At first it appeared simple, but the machine is still in the experimental stage. We had considerable difficulty with the feed, on several runs, which made it necessary to repeat the operation before satisfactory runs were obtained. We also had great difficulty in impregnating our samples with plastic in order to make studies of the fabric or orientation of the particles in space. We are about at the stage where we hope to produce results. I don't know how soon it will be but it should be the next three or four months.

QUESTION (Col. Bekker): Do you contemplate to investigate the stress-strain relationship?

ANSWER (Trask): We have investigated the stress-strain relationships in cooperation with the soil mechanics department. We take a vertical aspect and a horizontal aspect. We feel that the horizontal sectioning is equivalent in all directions; therefore, we do not take three-dimensional analysis. We have tried to apply the fundamentals of mechanics which you use in your Land Locomotion Laboratory. One more word: I think we have the techniques for studying the fabric of sediments and hope we are going to find some very interesting things about the arrangement of particles in space and thus produce information of use to Colonel Bekker.

QUESTION (Bramhall): What geological techniques are you using in the construction of these trafficability maps that the Corps of Engineers is putting out? I think these are related in a general way to Dr. Trask's previous data.

ANSWER (Trask): I don't think I can answer that question. Mr. Foster and Mr. Knight of the Corps of Engineers would have better information.

(Foster): I had an opportunity of talking with Dr. Bramhall before he asked the question, and the answer is that we use every bit of information which is available. We use geology, air photos, and we put penetrometer readings and/or boring data so that you might get the best possible map.

QUESTION (Bramhall): Are geologists working on the development of these techniques?

ANSWER (Foster): Yes, the map you see on the wall was based on work by Mr. John Shoot. We also employed Dr. Johnston from Purdue University. We couldn't attempt to do this kind of work without geologists.

DISCUSSION (cont)

QUESTION (Bramhall): Do you think that the geological techniques are at this time so advanced that we can use them for prediction of trafficability?

ANSWER (Foster): The opening statement by Dr. Trask's paper carried more truth than most of us realize. The problem is so complex and the material so variable, that you cannot get much accuracy of these measurements. The strength of the ground depends on the climatic and geological environment and is effected by the rainfall. What we can try to get is to predict only the ranges of strength that exist in typical conditions. At the moment we are studying the ranges and this constitutes our major effort.

DISCUSSION (cont)

QUESTION (Bramhall): Do you think that the geological techniques are at this time so advanced that we can use them for prediction of trafficability?

ANSWER (Foster): The opening statement by Dr. Trask's paper carried more truth than most of us realize. The problem is so complex and the material so variable, that you cannot get much accuracy of these measurements. The strength of the ground depends on the climatic and geological environment and is effected by the rainfall. What we can try to get is to predict only the ranges of strength that exist in typical conditions. At the moment we are studying the ranges and this constitutes our major effort.

EFFECT OF GEOLOGIC AND GEOGRAPHIC FACTORS ON SOIL TRAFFICABILITY

Parker D. Trask

Abstract

Soil trafficability is a function of soil strength. Soil strength depends upon the physical and chemical constitution of the soil and upon the things that have happened to the soil after it has formed. That is, the strength depends upon the composition and the geologic history of the soil. Compositional effects include average grain size, grain-size distribution, grain shape, surface roughness of grains, fabric (arrangement in space of constituent particles), friction of grain against grain, water content, capillary action, pore space, permeability, clay mineral content, type of clay minerals, organic content of the organic clay minerals, electrical (or polar) charges on grains, ionic concentration, reducing potential, internal friction and cohesion. Geologic history effects include growth of new minerals, base exchange effects, consolidation (or compaction), chemical precipitation, and leaching. In the coarse soils - sand and gravel - strength is essentially a question of internal friction, whereas in the fine soils - silt and clay - it is a function both of internal friction and cohesion. Internal friction is largely a question of physical contact of grain against grain, cohesion is a function of plasticity and colloidal properties of fine constituents. The strength of soil also depends upon its mode of origin. Mode of origin is essentially a function of the environment in which the soil is formed. Environment depends upon five principle factors, which to some extent are mutually interrelated: (1) climate, (2) topography or relief of land, (3) bed-rock geology, (4) biologic activity, and (5) time or geologic history. The problem confronting persons interested in the relationship of soil trafficability to soil strength is to evaluate the relative effect of the individual factors influencing soil strength under different environmental conditions.

CURRICULUM OF AUTOMOTIVE ENGINEERING

E. T. Vincent

Abstract

The paper deals with the present situation in Automotive Engineering at the Graduate level in most Universities, and particularly at the University of Michigan, where a new Automotive Laboratory is being built.

The requirements for Service Personnel in this field are discussed, as compared with civilian students. It is concluded that a special program for the Armed Services could be justified. Included in such a program should be Power Plants, Transmissions, Suspension, Vibration and Ride, Fatigue and Advanced Stress Analysis as applied to Engines, Bodies, etc., together with the fundamentals of modern automatic controls and computers, of interest to the Ordnance Corps as well as a modern course on Soil Mechanics as applied to Mobility.

COMMENT BY H. J. BENNER

1. Professor Vincent in his most interesting presentation brought up an important point: the development of a curriculum for automotive engineers, which would be of interest to the Ordnance Department of the Army.

As I have had some experience in this subject during the past 20 years, I would like to take this opportunity to share with you gentlemen, some views on this, extremely important problem.

During my work with the Operations Research Office at Johns Hopkins University we had occasion to circulate a questionnaire among some 80 Universities and Colleges which teach automotive subjects.

As a result of this inquiry we learned that the center of gravity of the curriculum, as far as professional attitudes are concerned, lies in the internal combustion engine and in the thermodynamics of respective phenomena. The problem of mechanics of locomotion as such appears non-existent for practical purposes. It is only casually and sporadically treated in various topics of applied mechanics.

Likewise, research work performed in automotive engineering by the schools has been concentrated primarily on fuels and lubricants. For instance, in 1952 over \$600,000 was spent on this type of work. Occasional research on the dynamic behaviour of an automobile consumed approximately \$75,000. Mechanics of Locomotion in a broad sense was studied at only one college; I am pleased to say that it was the college at which this Symposium is being held: the annual budget was about \$85,000.

Thus it is obvious that automotive engineering has not as yet organized a study of land locomotion mechanics, in a similar manner, for instance, to that in which aeronautical engineers or naval architects have organized their study of fluid dynamics. Automotive engineers do not take courses in soil and snow mechanics, and usually pay little attention to such problems as the theories of plasticity, or specialized branches of mechanics applied to such dynamic systems as moving vehicles.

What Professor Vincent proposes is to change this unfavorable situation by introducing an appropriate curriculum. Dr. Vincent assumes logically that such a program would be vital to the military services, and quotes precedent established by the Air Force which is now supporting special curricula in guided missiles, if I am not mistaken similar curricula exist in nuclear power, electronics, etc.

There is little doubt that a change in the present educational trend is necessary. The Land Locomotion Research Laboratory of Detroit Arsenal faces serious difficulties in finding appropriate personnel. I believe and my colleagues will support me, that the present educational background of automotive engineers is unfavorable, not only in the performance of research at any Land Locomotion Laboratory, but also at any proving ground,

or development agency striving to produce better mobility.

Accordingly, it seems that the need for a readjustment of the curriculum of automotive engineering along the lines suggested by Professor Vincent is of interest not only to the military services but also to civilian industry.

The volume of cross country equipment sales for agriculture, forest industries, road building and construction industries almost reached a billion dollars last year. The program of future highway development calls for further intensification of that effort. Improvements and economies which may be visualized through appropriate training of engineers are enormous.

Within my limited knowledge of prevailing conditions, I would estimate that at this moment between 200-300 automotive engineers trained in new techniques of mobility could be immediately absorbed by the proving grounds and test laboratories of automotive industries, the tire industry, Army Field Forces, Air Force and Navy if there is a clear cut recognition for the application of new methods and new tools. As such recognition becomes more and more distinct the basis for a new training program not only for the military but also the civilian students appears to be real.

During the past 13 years of my work in mobility, I have become convinced that the lack of such training and consequently the non-existence of a professional group has been the main handicap to our progress.

I would even venture to say that the future of research on mobility does not rest as much on the continuation of the present status, as it rests on the influx of new talent, new men, and new professional effort.

It appears certain that the best way to secure these favorable conditions is to start appropriate training of the younger generation.

REPLY TO M. G. BEKKER'S COMMENTS

Colonel Bekker's view on a suitable curriculum has been read with interest. I am in agreement with him that much has been left undone at the universities in the broad field of Automotive Engineering.

This is the reason why we at Michigan are taking the opportunity afforded by the construction of a new Automotive Laboratory to provide for the attack of problems outside those of the power plant; the body, chassis, etc. This is just a beginning and, given the demand, I am sure that the Administration would look favorably upon further extensions in all fields that would add to the basic knowledge of the subject. This is particularly important since, as Colonel Bekker points out, cross-country operation is not now a field of interest to the Military only.

Colonel Bekker's support for the development of such a curriculum is appreciated.

SCOPE OF ACTIVITIES IN LAND LOCOMOTION RESEARCH
FROM AN AUTOMOTIVE POINT OF VIEW

Lt. Colonel L. S. Nelson

Abstract

The trend of thought in present day vehicle design is to integrate a number of components, each of which has been well developed, into a vehicle concept. Of course, the objectives of the vehicle function are considered but the design of the finished product is predicated largely on the availability of the components. In effect, our vehicles are designed around the parts of which they are to be built.

The aim of the Land Locomotion Research Laboratory is to practically reverse our design thinking. We expect to furnish information which would lead to the design of vehicles capable of accomplishing the required objectives over certain definite types of terrain. This data would then lead designers to visualize new vehicles and then incorporate the essential components as secondary to the main objective. It may, indeed, encourage thoughts of new and radical components to satisfy the vehicle dimensions and requirements.

DISCUSSION

QUESTION (Bramhall): The Corps of Engineers has been interested in finding new methods of soil consolidation and making soft ground a hard one. If this were possible under all circumstances, we could make roads whenever necessary, and there would be no need for special vehicles. Colonel Nelson mentioned fork-lift trucks used in Korea were stuck in mud and could not operate. Why have these chemicals never been used for soil stabilization?

ANSWER (Nelson): I do not know why chemicals were not used to stabilize soil in that area. After the war was over, around August 1953, the Engineers did hard top (Macadam) sufficient areas (Receiving and shipping) to make it possible to use the standard fork-lift trucks.

The problems can be solved by one or both of the following methods: (1) That fork-lift trucks be designed to carry a pay load when operating over adverse soil conditions, or (2) That the soils be stabilized by chemical or other means to create a hard surface on which to operate the trucks.